Robustness in train scheduling

Master thesis

IMM, DTU

Mads Andreas Hofman
Line Frølund Madsen

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Abstract

In this project robustness in train scheduling is examined. The project is conducted for DSB S-tog because the current situation is influenced by a large amount of disturbances which cause delays and low regularity. The aim of this project is to help DSB S-tog in the development of more robust timetables. The robustness analysis is performed by comparing different already existing and new timetables using simulation. The approach of simulation of timetables is new in connection with DSB S-tog.

A generic model of the S-train network is modelled and implemented using the simulation tool Arena. The model can simulate all arrivals and departures of the trains in the entire network during a day. The model includes an implementation of three different recovery methods where trains are turned at a station prior to the end station, replaced at the central station or entire lines are cancelled in order to eliminate delays.

Distributions of the delays occurring at the stations in the S-train network are generated from historical data for the experiments. A number of experiments are conducted and investigated. Experiments include examination of the effect of the different recovery methods, investigation of the consequences of delays and comparison of how different features in the timetables affect the robustness.

The results from the simulation show that generally the robustness decreases as the number of lines in the timetable increases. Furthermore it is proven that the number of lines is not the only important aspect when developing robust timetables. Buffer times at the terminal stations have a significant impact on the robustness and it is also shown that the amount of necessary buffer needed to create a robust timetable is limited. The allocation of buffer times is important since all lines should be able to recover using buffer times. Furthermore line structure also turns out to have an impact on the robustness.

Finally two totally new timetables with new line structures are developed in this project. They both generally achieve an improved robustness.

Resume

Dette projekt omhandler robusthed i køreplaner. Projektet er udarbejdet for DSB S-tog, fordi de er i en situation, hvor store forsinkelser fører til en lav regularitet. Formålet med dette projekt er at hjælpe DSB-S-tog med at generere mere robuste køreplaner. Robusthedsanalysen er udført ved at sammenligne forskellige køreplaner ved hjælp af simulation. Indgangsvinklen med at bruge simulation er ny for DSB S-tog.

En generisk model af S-togs netværket er modelleret og implementeret i simulationsprogrammet Arena. Modellen kan simulere alle ankomster og afgange i hele netværket over en dag. Ydermere er tre forskellige genopretningsmetoder inkluderet i modellen; en hvor toge bliver vendt før endestationen, en hvor toge bliver erstattet på Københavns hovedbanegård og en metode, hvor hele linier bliver aflyst.

De forsinkelser, der bliver påført i modellen følger fordelinger, der er genereret udfra historisk data. Flere forskellige forsøg er udført og evalueret. Der er eksperimenteret med hvilken indflydelse de tre genopretningsmetoder har på forskellige køreplaner, hvordan forskellige forsinkelser påvirker regulariteten og forskellige køreplaner bliver sammenlignet i forhold til robusthed.

Resultaterne fra simulationen viser, at jo flere linier en køreplan indeholder, jo lavere bliver robustheden. Det viser sig ydermere, at mange andre faktorer har indflydelse på robustheden. Buffertid på endestationerne har for eksempel stor indflydelse på robustheden af en køreplan. Det viser sig også, at fordelingen af buffertid er vigtig og at der er en øvre grænse for, hvor meget ekstra buffer tid der er nødvendig, for at lave en robust køreplan. Derudover har liniestrukturen i køreplanen en effekt på robustheden.

To helt ny køreplaner med en anderledes linestrukturer er også udviklet. Disse giver begge en forbedret robusthed.

Acknowledgment

This project is made in cooperation with DSB S-tog. We would like to thank the department of production planning at DSB S-tog in general. Everybody have been very helpful. Specifically we would like to thank Jens Clausen, Julie Jespersen, Morten N. Nielsen and Claus Ørum-Hansen for their interest in the project.

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Mads Andreas Hofman

Line Frølund Madsen

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1 Problem formulation

This project is made in cooperation with DSB S-tog because they have a situation with unstable timetables. The timetable without any modifications is only used a few days every year, the rest of the time the timetable is modified because of unpredictable disturbances. These changes can be of smaller or bigger dimensions, but a lot of work is put into the modifications of the timetable. The goal for DSB S-tog is to be able to develop more robust timetables.

2 Project description

The objective of this project is to gain knowledge about the construction of robust timetables. This is done by testing certain hypotheses regarding the stability and robustness of timetables. A robust timetable should be able to recover from disturbances without having to re-arrange the whole plan. Robust means that the performance of the system is less sensitive to deviations from the scheduled timetable. Robustness is measured by categorizing a timetable according to a regularity measure, concerning percentage departures on time but also how well the original timetable can be re-established when disturbances have occurred.

In the process of planning a new timetable, one way of constructing a robust timetable could be to create a number of different plans and then use simulation to determine which timetable is the most robust. This process is very time consuming and therefore not suitable in the short term planning process. In this project timetables with different features will be examined, and the results should help ease the process of developing robust timetables. The timetables will be examined by building a simulation model of the train network and investigating the results from different simulation scenarios.

The aim of this project is to get an impression of what effect different features in timetables have on the robustness. Robustness of timetables will be measured by systematically simulating multiple timetables affected by disturbances. The main objective is to indicate factors in the construction of timetables, which influence the robustness of the plan. The affected timetables also have to be re-established in order to evaluate how well they recover. A secondary objective of the project is to study different approaches for recovering, once a disturbance has occurred. The idea is to test and compare different recovery methods. A final purpose of the project is to investigate the simulation tool Arena.

3 Report review

The first phase of the project concerns the process of gaining knowledge about relevant subjects such as simulation, railways, disturbances and recovery methods. In chapter 4 different concepts concerning robustness, railways and simulation are presented. A company profile of DSB S-tog is given in chapter 5. This chapter is followed by an examination of simulation in general and alternative evaluation methods in chapter 6. Furthermore it is described why simulation is used to evaluate timetables in this project. Design of timetables is examined in chapter 7, circulation of rolling stock in chapter 8, disturbances and delays in chapter 9, and finally recovery strategies and recovery implementation methods are described in chapter 10. These four chapters address the general cases, the specific situation at DSB S-tog is described later in the report. Existing literature about railways, simulation, reliability and recovery strategies is studied to gain knowledge about terminology, research results from already completed projects and also to get ideas for the modelling and experiment phases in this project. Summaries of the studied articles are given in chapter 11. In the chapters 12 to 14 the subjects of design of timetables, circulation of rolling stock, disturbances and delays and finally recovery strategies and recovery implementation specific for DSB S-tog are examined.

The second phase of the project involves the simulation tool Arena. A model of the S-train network will be developed in Arena. This is an important phase, because an additional objective in the project is to study the simulation tool Arena and also because the more precise the model the more useful the results of the later simulation will be. A description of the features in Arena and the modelling process is given in the chapters 16 to 18.

The next phase is the process of gathering data for the experiments. The data needed for the experiments are timetables with different features according to robustness and costumer service. Since DSB S-tog have not made bigger changes in the timetables over the past 10 years, only a few very different timetables are completely developed and directly available for this project. Therefore a part of the project concerns developing new timetables. The timetables used for the experiments are examined in chapter 19.

The fourth phase of the project is the simulation phase. In this phase different timetables are simulated and experiments with disturbances and different recovery methods are conducted. Furthermore a number of hypotheses regarding robustness are examined. The results of this phase are the actual objectives of the project. This phase is described in the chapters 20 to 23.

The final phase is the evaluation and conclusion of the experiments and the project.

The data used in the experiments are included on the attached CD-rom.

4 Concepts

In this chapter some useful concepts are described. These will be used throughout the report. The concepts are inspired from the literature, but since the meanings of some of the concepts are somewhat diverse, the specific interpretation in this report is given.

4.1 General concepts

Robustness: Robust means that the performance of the system is less sensitive to deviations from the scheduled timetable.

Regularity: Regularity is calculated as the percentage of departures on time.

Reliability: Reliability measures the number of actual departures from the stations compared to the scheduled number of departures.

Disturbance: A disturbance is typically defined as a delay above a certain size e.g. more than 2.5 minutes lateness.

4.2 Concepts concerning rolling stock

Rolling stock: Trains are often described as rolling stock.

Train unit: A train unit is a number of carriages and a locomotive. Different subtypes of train units might have different numbers of carriages.

Train type: Train type depends on e.g. the type of fuel the train uses or the age of the trains.

Train series and lines: A train series is defined by two terminal stations and all the stations in between. A train line is covering a train series but the train running the line does not necessarily stop at all the stations between the terminal stations.

Shunting: Sometimes during the day, for example outside rush hour, not all the available rolling stock is used. To fully use the railway infrastructure by the running trains, the redundant trains are parked in a shunt yard. The process of parking a train is called shunting. In this project shunting covers both turning at terminal stations and actual parking of trains.

Marshalling: Marshalling is the procedure of either connecting or separating train units to generate larger or smaller trains e.g. before and after the rush hour. Marshalling generally includes shunting of the train units before connection or after separation.

Merging: Merging of lines is the action of switching between lines i.e. the train covering one line is changed to covering another line, at a terminal during the circulation. Merging has the purpose of reducing waiting time at the end stations and thereby reducing the total number of trains necessary to run a plan.

Infrastructure: The infrastructure is defined as the entire network on which the trains are applied.

The infrastructure includes the stations, the tracks, the shunt yards, the signals etc.

Headways: The time between two consecutive trains traversing a point in the network. Minimum headway is the minimum time between consecutive trains, which must be observed according to safety. Minimum headways are sometimes referred to as safe headways. Planned headways are the times between the departures for the different lines in the timetable.

Dwell time and running time: The dwell time is the time a train is waiting at a station i.e. the duration of the stop at a station. The running time is the scheduled driving time from one station to another (or between two points in the network).

Buffer time: Buffer time, also referred to as slack time, is the extra time which can be incorporated into the timetable to be able to maintain scheduled departure and arrival times when delays occur.

Cycle time: The period of time it takes for a train to complete a tour from a terminal station and back to the same terminal station.

Primary and secondary delays: Delays can be split into two categories. When disturbances occur on running times or dwell times the resulting delays are called primary delays. Primary delays are initial delays caused on a train from the outside and not by other trains. To reduce the delays the timetables contain buffer time. But when buffer time is too small a cause of delay on a train may give rise to a conflict with another train. These delays are called secondary delays. Secondary delays are delays of trains caused by earlier delays of other trains. Primary delays are also called source delays. Secondary delays are also referred to as knock-on delays.

Repositioning trip: Transportation of trains without passengers. Also referred to as *dead heading.*

4.3 Concepts concerning simulation

Simulation model: A simulation model is a computer model of a real system, with the purpose of illustrating the behaviour of a well-defined system.

Simulation: Simulation is to solve a problem by experimenting with a simulation model. A *batch simulation* is a series of simulations, where a series of experiments are run, to solve a given problem.

Static vs. dynamic simulation: Time does not play a role in static simulation but does in dynamic simulation. Most operational models are dynamic.

Continuous vs. discrete simulation: In a continuous simulation the state of the system can change continuously over time e.g. water running out of a tank. The basis of the continuous simulation is that the simulation time is increased by one constant time increment at each simulation step. After each time increment, the state changes occurred during the previous time interval are calculated. When continuous simulation follows the clock it is called *Real-time simulation.* In a discrete simulation changes can occur only at separated points of time. Discrete simulation is controlled by events, and the state changes are updated after every event. Sometimes elements of both types are combined in a simulation.

Stochastic vs. deterministic simulation: A Stochastic simulation involves randomness or probability. Stochastic simulation can be used to e.g. analyse the effect of certain faults (randomness) applied to the system. A deterministic simulation model is not influenced by these external factors. Deterministic simulation is often used to illustrate a system for the sake of e.g. learning.

Iconic simulation models vs. logical simulation models: An iconic model is a physical replica or scale of the system. A logical model is a mathematical model which builds on approximations and assumptions about the way the system will work. If the logical model is valid it should reflect the actual behaviour of the real system.

Macroscopic vs. microscopic simulation: A simulation model is categorized as either macroscopic or microscopic depending on the level of detail. If the simulation model is an exact representation of the real system the model is microscopic, but if details like signals, weather or human behavior are omitted the simulation level is macroscopic. In the case where all materialistic details are implemented and only human behavior is omitted the level of detail is called mesoscopic.

5 Company profile

In this chapter a description of the company DSB S-tog will be given. Figures and statistics are mainly taken from the DSB S-tog Annual Report 2004 [5].

DSB S-tog A/S is a company within the DSB Group, the Danish State Railways (DSB), the company which runs most of the trains in Denmark. DSB S-tog operates the S-train network which is an important part of the public transportation system in the Greater Copenhagen area. The public transport network in Copenhagen also includes busses, metro and a number of small train networks. The traffic network also includes regional and international train connections. Regional trains link with the S-trains at some of the larger stations e.g. Høje Taastrup, Valby, Hellerup, Nørreport and København. The S-trains intertwine with the metro at Nørreport, Vanløse and Flintholm stations.

DSB S-tog has the responsibility of planning and implementing timetables for the S-trains and is in charge of quality control and maintenance of the trains. DSB S-tog is also responsible for environmental issues, logistics, purchasing, safety works and the development of technical train solutions. Besides planning and running the S-trains DSB S-tog also plan and schedule the crew which run and maintain the S-trains. On the other hand DSB S-tog is not responsible for maintenance of track, signals, stations, security systems etc. which is taken care of by BaneDanmark, a company run by the Department of Transport and Energy in the Danish government.

The S-train network consists of 170 km double tracks and 80 stations. The network is constantly occupied by approximately 80 trains during the day and there are 1100 departures daily. The S-train network is displayed in Figure 1. The figure shows the stations, the train series and the lines in the current plan. The numbers in the figure refer to the different zones relating to the cost of travelling.

There are 5 main train series in the S-train network; Køge-Hillerød, Høje Taastrup-Holte, Frederikssund-Farum, Ballerup-Klampenborg and Ny Ellebjerg-Hellerup. The train series are covered by different lines, indicated by different colours and the capital letters A, B, C, E, F, and H. For example the train series between Høje Taastrup and Holte is covered by the green line B. The line B^+ is also covering the train series between Høje Taastrup and Holte but this line is only used during daily hours. This is the case for all the +-lines. The x-lines are only used during the rush hour in the morning and in the afternoon. All the lines have a frequency of 20 minutes and are run according to an hourly cyclic timetable. When more departures are needed to fulfil the demand, extra lines are used to cover the series. This explains the +-lines and the x-lines. Main lines and extra lines, e.g. B and B^+, are run with 10 minute intervals. The lines F and F^+, covering the train series between Ny Ellebjerg and Hellerup, is called Ringbanen because it runs around the city.

As all trains in the network travel from one end station to another in the train series, the distance between København (Copenhagen central station) and Svanemøllen defines a bottleneck. Since all trains (excluding Ringbanen) has to travel through this part of the network and the frequencies on all lines are 20 minutes there is a limit on the number of trains passing this section. Currently the headways in the central section are scheduled to be 2 min. and the frequency is 20 minutes, hence a maximum of 10 train lines can traverse the tracks from København to Svanemøllen (in practice the minimum safe headways in the central section are 90 seconds). DSB S-tog and the Minister of Transport have signed an agreement of construction a sixth main track south of København station, expected to be commissioned by 2007. This should have an effect on regularity and also on restoring the balance following irregularities.

Figure 1: The S-trains network

Figure 2 shows the 10 largest stations in the S-train network, with regards to the number of arriving and departing customers in a typical day in 2004. As shown in the figure København (Copenhagen) and Nørreport are the two busiest stations.

5.0.1 Customers

The customers using the S-trains are the largest group of customers for DSB. The S-trains serve around 90 million customers a year, i.e. 240,000 customers use the S-train network each day. On the

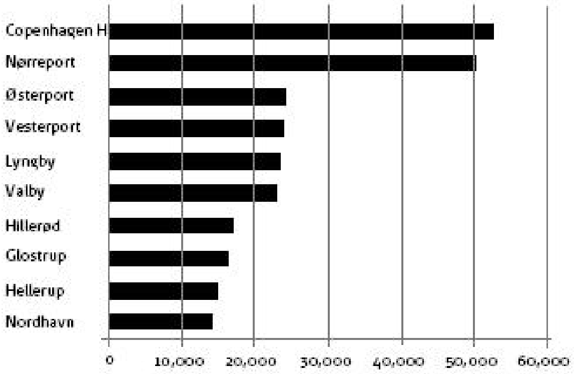


Figure 2: The 10 largest stations in the network with regards to number of arriving and departing passengers

average 92% of the population in the Greater Copenhagen area use the S-trains to some extent. So DSB S-trains have approximately 1.4 million customers in the Greater Copenhagen area.

In Figure 3 the number of passengers in each month of 2004 is shown. The largest customer group for the S-trains are customers travelling to work, school or other educational institutions. In Figure 4 the number of passengers in each hour of a typical day in 2004 is shown. As seen in the figure the rush hour is approximately from 6:00 to 9:00 in the morning and again from 15:00 to 17:00 in the afternoon.

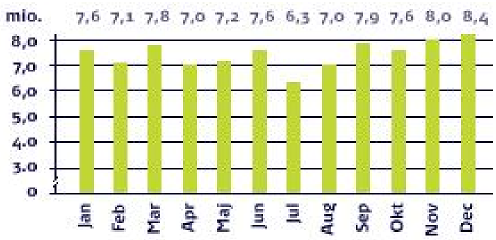


Figure 3: Passengers in 2004

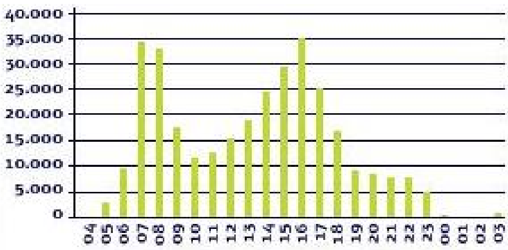


Figure 4: Passengers during a day in 2004

6 Simulation

The study of robustness in timetables can be approached in different ways. Some problems can be solved by several different approaches. In this chapter the method of simulation will be described. In section 6.1 an elaboration on why simulation is used in this project is presented. Finally in section 6.2 a short description of a group of alternative solution methods will be given.

Simulation is a collection of methods to imitate the behaviour of a system. Simulation is the process of designing and creating a computerized model of the real system for the purpose of conducting experiments to give an understanding of the behaviour of the system. The modelling itself is crucial to the outcome of the experiments, since the outcome depends on the representation in the model as well as the analysis. Therefore as many data and details should be collected for the modelling, since a higher level of detail will give more accurate results, even though it is sometimes at the expense of longer running times for the simulations.

An advantage of simulations is the ability to deal with very complicated dynamic models of correspondingly complex systems. As opposed to analytical methods simulation can be used to get a precise picture of a given situation. Simulation can also be used to test different values of parameters, to analyse the results of parameter tuning. Simulation requires entire data sets of the system to display the development in the system. In contrast to analytical methods a simulation tool does not give a solution as output. By repeating the simulation (batch simulation) the results can be evaluated and improvements for the situation might be seen. The drawbacks of simulation, contrary to e.g. analytical methods, is that it is very time consuming and requires very detailed data sets as input. Furthermore simulation does not result in an optimal solution (or at least there is no way of testing whether a solution is optimal). In many situations changes in plans occur frequently both for long term, medium and short term plans, therefore simulation might be too time consuming to be used as a decision tool. Simple quickly computed heuristic measures or rule of thumbs can be used instead. However simulation is the best method to use when reliable and trustworthy results are needed. As for railway systems simulation methods give the most detailed representation and today simulation is the only reasonable way to model the details of the complex interaction between different trains and the interaction between the trains and the infrastructure.

Simulation can be used both as a learning tool and as a planning tool. Generally there are three purposes of simulation:

- Educational purposes (learning tool)
- Evaluation of an already existing system (planning tool)
- Planning of a new system (planning tool).

When simulation is used as a learning tool, the model is used by the operator, to possibly learn how to operate the system in real-time conditions. An example of simulation where the purpose is education could be a flight simulator used for testing skills and ability to respond for pilots. When simulation is used as a planning tool it is most often used for experimenting with different scenarios with the purpose of obtaining an optimal or best plan for the system e.g. layout and production schedules. Evaluation of an already existing system is e.g. testing the consequences of producing more products in an already existing production assembly line. Finally simulation in connection with planning a new system could be to find a good solution when planning a new production line e.g. testing throughput time for the product with different arrangements of the machines. In this report only the purpose of evaluation of a already existing systems will be investigated.

When dealing with simulation the level of detail chosen is of great importance to the outcome of the results. It is very important to determine how many detail are necessary for the specific simulation project. The necessary level of detail depends only on the purpose of the simulation and the use of the results. A simulation model is categorized as either macroscopic or microscopic depending on the level of detail. In this project only macroscopic simulation will be considered.

A simulation project, like many other projects, can be split into several phases:

1. Problem formulation. First the problem must be specified precisely. It is also very important to make sure that all parties understand and agree on the problem formulation.
2. Data. Determine whether enough data is available and collect the necessary data.
3. Assumptions. Determine if it is possible or necessary to build a model of the entire system or if limitations or assumptions can be made. The level of detail should be specified.
4. Solution methodology. Determine how the given problem can be solved and whether it is possible to solve the problem by simulation given the obtained data.
5. System specifications. In this phase information about the system is collected. To build a simulation model, a good understanding of the system is required.
6. Model formulation and construction. Considerations about how the model should be build and actually building the model.
7. Verification and validation. Examining whether the model is behaving as expected (verification) and behaving in the same way as the real system (validation).
8. Experimentation and analysis. Running the simulation and analyzing the data according to the desired output.
9. Results and conclusion.

6.1 The use of simulation in this project

The reason for using simulation in this project is that DSB S-tog wishes to have a general robustness measure developed. The robustness of a timetable depends on the entire S-train network. The network is dynamic and it is not predictable what will happen if changes (disturbances) occur. To get an accurate picture of how different factors influence on the system, simulation is used. Because all the factors in the network can influence on the robustness, simulation will give the most accurate result and therefore also the best result. Simulation is very time consuming and is therefore not necessarily the best decision tool in the short term planning process. This is also the reason why DSB S-tog cannot use simulation every time decisions have to be made. Instead simulation is used in this project to test certain hypotheses regarding robustness in timetables, which can be applied when new timetables are developed.

This project deals with dynamic discrete stochastic simulations. The simulation model of the S-train network is dynamic because time is an important factor in the simulation. The simulation model is discrete because it is build up around events such as departures, arrivals etc. Finally the simulation model is stochastic because possible delays are not constant.

The simulation model build to simulate the S-train network is build with a macroscopic degree of detail. This means that the model does not concern signals in the network, human behavior etc. Furthermore there is no differentiation between different type of trains, which might have i.a. different speed limits.

6.2 Alternative evaluation methods

In the literature on train scheduling, evaluation of timetables is approached in different ways; some authors are concerned about the scheduled and the actual waiting time, some connect the slack time with capacity utilization and yet some look at the delay propagation. The methods used for the research are also different. In the following sections a group of methods, which are alternatives to simulation for studying timetables according to robustness, will be presented.

6.2.1 Analytical methods

When using an analytical method a mathematical model is developed using some or all available data for the system. Analytical methods are often used to find optimal or near-optimal solutions to given problems. Depending on the input data, analytical methods are used for different measures like delay or cost analysis. Analytical methods are often mathematically demanding, but do not require much input, in many cases they can be used without knowing the exact timetable. Because the input data is sparse the methods often make a lot of assumptions, which results in less reliable results. The computational time for analytical methods is usually rather small, hence these methods are good for quick evaluations and many different solutions can be evaluated within a short range of time. For this reason analytical methods are of good use when planning future investments, where uncertainty and lack of realistic input and knowledge is dominating the situation. Analytical methods are used for strategic decisions in the early planning process and are usually only practical for very simple structured systems. An example of an analytical method could be the max plus algebra described in [8] and used to evaluate the performance of a timetable. Another example of an analytical solution method could be the solution of a periodic event scheduling problem which is used to solve problems of periodic timetabling see e.g. [14].

6.2.2 Heuristic methods

Heuristic methods are a subgroup of analytical methods. Heuristic methods are often used to evaluate more complex systems. Some methods can be used in advance e.g. for estimating the reliability of a proposed schedule or changes in a schedule at the design phase. Some methods build on information about probabilities and distributions of delays and require these as input. Other heuristic methods deal with designing optimal timetables. The models developed are also mathematically complicated, usually relying on heuristic techniques for integer and non-linear optimization. These methods can also be used as decision support to re-schedule trains in real time when delays have occurred.

The most interesting methods, especially for planners, are the methods of expected regularity and reliability which can be estimated in advance. These methods can be of use to consider new schedules or changes in service.

Several heuristic methods can be calculated in advance e.g. the probability that a train does not suffer from secondary delays and the aggregate reliability for a set of trains. For examples on specific heuristic methods based on the probabilities of delays see [3].

A number of methods that do not use probabilities also exist. These methods consider e.g. minimum headway targets and variance and standard deviation for headways. In examining reliability it is important to consider both primary and secondary delays. Secondary delays can be reduced by better scheduling. The methods above use the proposition that the probability of secondary delays are at minimum when the headways are equal of size. This is an important proposition, since the aim is to minimize secondary delays, in order to improve the reliability and regularity.

In practice heuristic method calculated in advance may differ significantly from actual reliability or regularity. However if the methods systematically under or overestimate the actual data, the methods can be used by compensating by some correcting factor.

7 Planning and design of timetables in general

The planning process of a railway network can be divided into several phases. Starting from a market demand, network planning is the first step in the planning process. The next phase is train series planning, which is the phase where train connections are determined, starting and terminal stations are chosen, including routes and the stations in between, where the train should stop. Train series planning is followed by timetabling. In this step departure and arrival times are set. There can be several iterations between these two steps if a preferred train series does not imply a feasible timetable. When the timetable is finished the rolling stock circulation is planned. This step also includes planning of shunting and repositioning trips. Both for the regular trips and for shunting train drivers have to be scheduled. The last step is crew scheduling.

In Figure 5 the planning process is presented as a flow diagram [23]. Because all the phases depend heavily on the preceding steps, it is sometimes necessary to go back in the planning process and perform changes, since a choice in a preceding step might have unforeseen consequences e.g. on the robustness of the final plan.

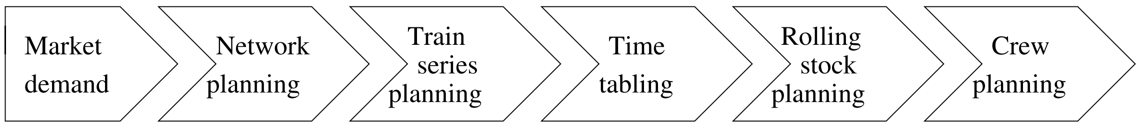


Figure 5: The sequence of interdependent railway planning phases

All phases of the planning process have consequences for the robustness of the final plan. The network planning has the effect on robustness that if there are more tracks in the network, overtaking might be possible in case of delays and disturbances, which reduces the probability of secondary delays. Train series planning and timetabling defines the number of lines and the frequency of trains, which naturally have an effect on the robustness, since less trains and lower frequencies will create larger time buffers. Furthermore in the planning of the timetable it is very important to allocate the lines as evenly as possible, with regards to planned headways, to ensure the best buffer times between trains in case of disturbances. The rolling stock planning also has an effect on the robustness. When a large number of different types of trains are used, these might have different speed limits etc. and therefore might require e.g. different headways which will result in heterogeneous running patterns, which again might result in a less robust plan when disturbances occur. In the rolling stock planning the required number of trains is also determined, and a larger number of trains with the same frequencies might results in better shunting times and possibilities of gaining more time because of larger time buffers, but of course also increase the total cost. Robustness in crew scheduling is also very important. In the situation where the scheduled crew are not available for departure the trains will be late, which also affect the robustness.

When studying the planning process it is not always necessary to consider all the phases, for example the phase of network planning can be considered fixed if the purpose is to study an existing network, where it might not be possible to change the structure of the network. Similarly if the purpose is to propose improvements in rolling stock planning it might not be necessary to include the aspects of crew planning. In this project only trains series planning, time tabling and rolling stock planning is considered.

7.1 Design of timetables

In the planning of time schedules for lines, many factors need to be considered. There is a high degree of interdependency since trains are sharing tracks, so schedules for different lines might depend on each other. A schedule for a line also depends on security regulations and speed restrictions etc. Naturally cost is a very important factor in the planning of line schedules, therefore timetables are often optimized according to a minimal use of train sets, since the number of trains used is one of the largest cost terms for running trains. On the other hand it is not necessarily recommendable to have an optimal plan with regards to cost and minimal number of trains necessary, since a small disturbance might affect the robustness of the whole schedule, and adjustments need to be performed all the time.

A way of creating robust timetables is to incorporate time buffers (slack). Robust means that the performance of the system is less sensitive to deviations from the assumed timetable. Large time margins will increase the robustness, but at the expense of longer travel times for passengers and the need of more trains. Another way of creating more robust timetables is to run fewer trains on a particular series. This will create larger time margins and hence less probability of secondary delays. Again the expected travel time will increase, which is a drawback for passengers. Scheduled headways between trains on shared stations should also be allocated as evenly as possible to ensure the largest buffer time between all trains.

Often the timetables are constructed to be cyclic. This means that passenger services are repeated every cycle time, usually every hour. Also in the planning of timetables it can be considered how good the connections between the trains are, such that train services at large stations fulfil that a passenger can change between trains with maximum waiting time at the station of e.g. 5 minutes. A timetable is designed to be feasible, in the sense that if no disturbances occur then there will be no delays. On the other hand if it is not possible to run all trains at the assumed speed, then delays will occur.

8 Circulation of rolling stock in general

In the following section the general procedures of planning circulation of rolling stock will be described. The circulation of rolling stock is the problem of allocating trains to the train series. The rolling stock allocation and circulation starts after the network has been planned, the required capacity has been determined and the timetable has been generated. The study of circulation of rolling stock is included in this project because it is closely connected to scheduling of trains.

The circulation of rolling stock is a very relevant optimisation problem, since the rolling stock represents a large capital investment. Also it is an investment that cannot be changed frequently. This makes the decision of how many train units should cover a train series in order to meet a certain customer demand very important. Also when railway companies experience a shortage of rolling stock capacity, it is important to look for the most effective allocation of the rolling stock available, to provide the highest level of service to the passengers and to ensure the robustness of the plan.

The objective of the rolling stock problem differs e.g. according to time of day. There is a difference between the operational problem of minimizing the number of train units given the allocation of trains to train series, and the tactical problem of finding the most effective allocation of the train types, so that as many passengers as possible can be transported with a seat. The objective can be to minimize the number of trains needed, to provide a certain service to the passengers or to minimize the carriage kilometres. In rush hour the objective is usually to satisfy passenger demands, such that as many people as possible can be transported. Typically outside rush hour the objective is to minimize the total number of carriage kilometres. The rolling stock problem can be solved for a single train series or for a set of interacting train series.

Marshalling and shunting of the trains are performed to satisfy the objective function, e.g. satisfy customer demand and also minimize the number of carriages. A train unit may be uncoupled from a train after the morning rush hour and then coupled again before the afternoon rush hour. In the process of marshalling and shunting the composition of the trains is an important issue. The composition of a train indicates the ordered sequence of train units. An example could be a morning rush hour train with the different train units X and Y. The composition of the train could be e.g. YXY or YYX. If one of the train unit, e.g. X, is scheduled to be coupled to another train during the afternoon rush hour it should not be located in the middle of the current composition, this would complicate the shunting and marshalling process.

The literature presents different models for solving the rolling stock allocation problem, see e.g. [1][2][18]. The models involve different aspects, such as passenger demand, different types of trains, shunting of trains, maximum length of a train, inventory position at the stations and the composition of the trains. The different models are focusing on different aspects. Shunting itself is a special optimization problem, concerning parking trains in the most efficient way in the shunt yard. The shunting problem is studied separately in the literature, see e.g. [21][13].

9 Disturbances in general

In this section the general causes of disturbances and delays will be described.

In a network as complicated as a train network many causes of disturbances can occur. Busy complex train stations with several platforms may have several hundreds of trains arriving and departing each day, serving thousands of passengers. Trains of different types arrive and depart on conflicting lines and are subject to restrictions concerning which platforms or lines they occupy. Therefore delays are common in connection with train scheduling. There is a connection between how a railway system is designed and how delays will occur and propagate in the system. The relationship can be determined by simulation of different timetables or by some form of sensitivity analysis. It is also possible to affect the risk of delays occurring, by the design of the timetable. To counteract for delays in train scheduling, slack time is usually incorporated into the train schedules when these are constructed. This slack time should help to stabilize the system and therefore reduce the propagation of delays in the network. The degree of occurrences of delays is also depending on the capacity utilization of the network, so if the utilization is high there is also a high probability of delays occurring.

Disturbances can be accidental or caused by planning problems. Examples of causes of accidental disturbances are:

- Delays in passengers boarding or alighting
- Signalling problems
- Operation delays or mistakes
- Failure of equipment or rolling stock
- Weather
- Accidents
- Obstacles on lines
- Crew lateness.

Examples of causes of disturbances caused by planning problems are:

- Line maintenance
- Seasonal or rush hour changes in demand
- Lack of capacity (trains or tracks)
- Heterogeneity in the timetable or in the train types
- Too high utilization of the system.

When disturbances occur, the stability of the system is affected. The stability change depends on the size of the disruptions, the number of disruptions and how robust the system is initially. If the system is robust small disruptions will not affect the stability and therefore no delays will occur. Figure 6 displays an example of how number of trains, heterogeneity and stability is connected [15]. The figure shows that stability decreases when the number of trains increase. When many trains are using the same tracks the risk of disruptions propagating and thereby affecting many trains increase.

Also when the heterogeneity factor increases, i.e. many different types of trains are being used or very dissimilar stopping patterns are planned, the stability of the system decreases. If the stability changes considerably, large delays will occur.

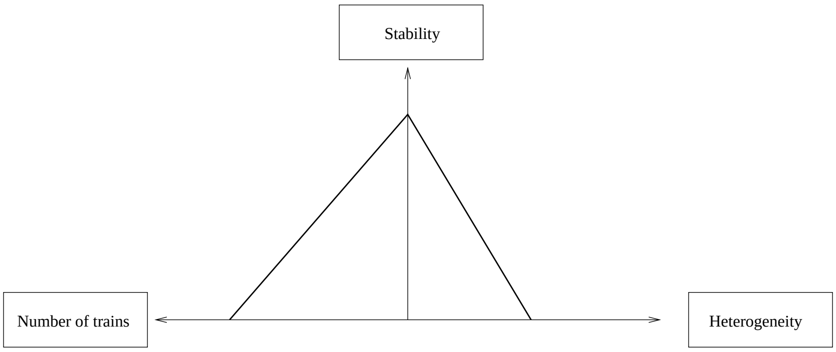


Figure 6: Stability balance

Delays can be split into two categories: Primary and secondary delays. Primary delays occur when a disturbance cause a delay on a single train. Primary delays cannot be eliminated and are independent of the design of the timetable. Primary delays are also in theory independent of capacity utilization, but analysis of the causes and locations of primary delays can be used to generate a reliable schedule, where primary delays cause the least secondary delays. This is possible since the occurrence of secondary delays is affected by the schedule design. When slack time in the timetable is too small a cause of delay on a train may create a conflict with another train. These delays are called secondary delays. For example if a train is late leaving a platform, this may delay the arrival of the next train scheduled to use the same platform, which may delay further trains. On the other hand if a train arrives late, the scheduled platform may be occupied, so the train has to be sent to another platform which may delay trains scheduled for that platform. It is important to keep primary delays down to a low level, otherwise secondary delays may quickly escalate, due to the interdependency in the train network.

9.0.1 Heuristic measures of reliability

When dealing with disturbances it is convenient to measure the effect of disturbances in the system. The effect of disturbances can be measured by the reliability of the system. Regularity is probably the most widely used reliability measure. Examples on heuristic measures of regularity are the percentages of service on-time, or more than 5, 10 etc. minutes late. Another example is the average lateness. These measures require information about train arrivals and departures, and can therefore only be calculated after the events. They can also be calculated from the observed probability distribution of the lateness.

To passengers the knowledge about regularity can be used in planning travel choices. Obviously both primary and secondary delays strongly influence regularity and reliability and thus are of importance to passengers. It is generally claimed that passengers perceive disturbances differently. Occasional large disturbances can often be accepted since they are accidental and in many cases can be explained. On the other hand everyday lateness of trains, which results in broken connections is not accepted, therefore these minor disturbances should be avoided. Another reason for avoiding too many small disturbances is that these may easily cause large delays over time. An important issue in connection with reliability is the door-to-door travel time, which means that it is not only the regularity of one train that is important, the connections to other trains are just as important, because it is the entire travel time the passengers are concerned about. If the connections are trustworthy it is easier for the passengers to plan their transport. To operators and marketing heuristic measures of reliability can be used to plan, manage, control and improve services. To the top management the measures are needful to check if operators deliver what they promise in terms of quality of service or contracted goals.

10 Recovery strategies and methods in general

As described earlier, many different types of disturbances may occur in the daily operation of railways. These disturbances can be dealt with in different ways; by re-establishing the original plan, by re-scheduling or by regaining regular headways. The three strategies will be examined in this chapter. The distinction between strategies is inspired from the different recovery strategies described in the literature see e.g. [10][7]. The different recovery strategies represent several recovery methods such as cancelling trains, replacing late trains or reducing minimum dwell times. An examination of different implementations of recovery methods is also made in this chapter.

10.1 Recovery strategies

Management by re-establishing the original plan

In this strategy the traffic controllers try to solve the problems by using the time margins (slack) build into the timetable. Connections between different trains may be broken, trains may be late, platforms may be changed, running times and dwell times may be reduced, but generally the plan remains intact. This strategy is usually used to deal with minor disturbances, since otherwise it may take too long to re-establish the original plan. Management of minor disturbances is usually predictable. There might be rules for how long a train may wait at stations for connections or rules to change order of trains if only one train is late. Two examples of how re-establishing can be used are given in the following.

When trains are late at arrival, reducing the dwell times can help trains get back on time. Suppose a train has a scheduled dwell time of 6 minutes and a minimum required dwell time of 3 minutes. If it arrives 4 minutes late, it can be ready to depart after 3 minutes, hence only 1 minute late instead of 4 minutes. On the other hand if the minimum dwell time is 1 minute, it is ready to depart after 1 minute, but of course it is not allowed to depart before the scheduled time, hence the train can leave on time after 2 minutes, and thereby the delay has been eliminated.

If trains arrive later than scheduled their assigned platform may be occupied by later trains. In this case the train could be held until the assigned platform becomes free. On the other hand it could also be send to another platform if one becomes free sooner. Similarly if a train departs late, the next train scheduled for the same platform can either wait until the platform becomes available, or go to another platform if one becomes free sooner. It should be noted though that these on-the-day changes in platforms may cause further secondary delays to the following trains if not done carefully, which should be considered before allowing changes. Experiments have shown that allowing the change of platform reduces secondary delays [4]. The strategy depends on how heavily congested the system is. If trains run on a very tight schedule it might not be such a good idea, to allow changes in platform, since this will disrupt a large number of trains. On the other hand if the schedules contain larger headways it might reduce delays considerably. The strategy also depends on whether all platforms are feasible for all train types. Furthermore there might be some restrictions due to the layout of the network, which might prevent the strategy from being possible. Regarding passenger satisfaction, it should also be considered whether it is convenient to get from one platform to the others.

Management by re-scheduling

In this recovery strategy trains or lines may by re-routed or cancelled. Essentially a new plan is made and the logistical plan is disrupted. The goal in the end is to re-establish the original plan but this may take several hours, or it might not even be possible within the same day. This strategy is used in operations when major incidents cause delays e.g. accidents or rolling stock failure. There might be rules on which train lines to cancel in case of disturbance or which lines to re-route. Even if certain rules exist for management of large disturbances, the outcome still depends very much on the exact circumstances and on the choices made by the operator responsible for traffic control.

Management by regaining regular headways

A third recovery strategy is to regain regular headways as quick as possible. After a disruption the affected trains may be clustered. Instead of waiting for the scheduled departure time for every train they are set off as fast at possible with the smallest possible headways. The idea is to get as many trains rolling as possible and maximizing capacity utilization. This recovery strategy is mostly used in urban rail network where the trains are scheduled to run within small intervals e.g. metro systems. On very busy stations the exact minute of departure is not of most importance because the frequencies of train departures are very large. If e.g. trains are running between two stations with an interval of 3 minutes it seldom matters to passengers exactly what train is reached. In longer term when the disruption is stabilized the trains are re-scheduled to the original plan.

10.2 Implementation of recovery methods

In this section two different ways of implementing recovery methods are examined. The first implementation method is referred to as an 'expert system', because a set of rules are used to recover when disruptions occur. The rules are derived from operational experience or the acquired skills of the control centerer staff. These rules can be implemented in a computer, written down in a rule book or just be in memory of the operators. Whenever the rules are developed this can be a quick method of determining a recovery solution, but the solution is not necessarily the best possible, and therefore it is important to evaluate the results of a recovery and the rules should be updated continuously.

The other implementation method is based on a mathematical model with an objective function and a search procedure. The objective function must optimize the recovery and the search procedure must be used to find the set of operation instructions that optimizes the objective function. This implementation method is often not very fast but gives an optimal solution. Furthermore it is not always straight forward to develop the objective function, to find an appropriate search procedure, or to model the appropriate constraints.

The difference of computer decided or train operator decided recovery is also of importance. When smaller disturbances are to be eliminated the decisions are often made by a computer system and for bigger disturbances train operators make the final decisions. The two implementation methods can also be combined.

11 Literature review

In the literature several related problems concerning planning and scheduling of timetables is treated. In this chapter a number of articles on the subject is reviewed. First some articles on simulation are reviewed. These are of great interest because simulation is the subject of this project. Then a number of articles describing reliability and measures of reliability are addressed. The articles are relevant in connection with measuring robustness of a timetable, since reliability can be used as a measure of robustness. Then a few articles about recovery methods are presented. Recovery is of interest in this connection because it is important to investigate how a timetable react when disturbances occur, and also to examine how easily an affected timetables can be re-established. Finally a couple of articles concerning allocation of rolling stock and shunting are included, because these article are proven very useful in gaining knowledge about terminology and understanding basic concepts within railway planning and timetable scheduling.

11.1 Literature on simulation

The use of simulation in the planning of the Dutch railway services

Hoogheimstra and Teunisse [10] describe their research on robustness in timetables in the Dutch railway network. The authors present their considerations about planning of the infrastructure and timetables. They also state the importance of reliability and punctuality. A program called DONS (Designer Of Network Schedules) is used to generate timetables. The goal of the paper is to determine if construction of timetables can be refined to increase the robustness of the operation. To attain this goal a DONS-simulator is developed. The simulation tool enables the authors to study the effect of small disturbances on the punctuality of trains in the entire network. The simulator will also be used to evaluate how investments in infrastructure effects punctuality in later research. This paper does not present the final results of the research. The paper only describes the building and testing process of a prototype of the DONS-simulator. In the following article “Simone: Large scale train network simulations” [16] the final simulation tool is described.

Simone: Large scale train network simulations

Middelkoop and Bouwman [16] describes the architecture and features of the simulation program Simone (Simulation Model Network). Simone is a simulation environment developed with the purpose of determining the robustness of a timetable and the stability of a railway network, and thereby improve the quality and stability of the timetables from a set of different criteria. It does this by determining bottlenecks in the network, by examining the number of delayed departures for all the stations in the network. Simone can also be used for analyzing delays and exploring causes and effects of delays for different layouts of railway infrastructures and timetables. Simone can simulate an entire railway network, compared to other models, studied in connection with the literature review in this report, which are limited to a smaller set of elements e.g. one train line or a small number of stations.

The article describes the Dutch rail network, for which Simone has been designed. Netherlands rail network consists of almost 600 stations (including junctions) and about 2750 kilometer tracks. Simone is used to compare the quality of different timetables. Quality in timetables depends on network properties such as correspondences between trains and use of shared capacity.

Central in Simone is the timetable, which drives the activities. When there are no disturbances all trains run according to schedule. When disturbances occur Simone inspects the different types of delays (primary and secondary) and the user gets extensive information on the delays and delay propagation in a specific simulation. Simone also provides other information and statistics on the states of the trains and stations in the model. This makes it useful for comparing the robustness and punctuality of different timetables.

The article also describes the architecture and functionalities of Simone in more details and shows some graphical representations of train networks. Also a case study for a specific station in the Netherlands is given in the articles. The case study shows some of the functions in the program.

The authors describe how Simone has been used on several different studies already with good results and that it proves to be a good research tool. It provides insight on the performance of different timetable and infrastructure combinations. An advantage is the possibility of simulation an entire railway network.

Simulatorsystem inom tågtrafikstyring, en kundskapsdokumentation

English title: **A train traffic operation and planning simulator within railways**

In the report [20] Sandblad et al. describe various concepts within simulation of train traffic for use in both planning and training. The article is an introduction to simulation in general.

They describe the development of a new simulator system which can contribute to improved methods for train traffic planning, experiments for developing new systems and training of operators.

The report explains the purpose of using simulation in train traffic planning in general. It also explains the difference between simulation as a planning tool and as a learning tool. There is also a thorough description of other purposes of simulation e.g. understanding the behaviour of the system, as a base for difficult decisions, or for controlling the system.

In addition the report describes the different phases in the planning and implementation of a simulation project. These include problem specification, construction of the model, validation of the model, programming, verification of the program, planning the experiments, realization of experiments, evaluation of results and conclusion.

The article includes many descriptions of concepts. Some of these concepts are symbolic models (which build on mathematical equations) as opposed to iconic models. Stochastic models contra deterministic models is also explained. Finally modelling time, continuous simulation vs. event simulation (discrete simulation), real-time simulation and batch simulation are described.

11.1.1 Comparison of the literature on simulation

The first two articles described in the previous section are both dealing with simulation used as a planning tool in the Dutch railway services. The first article describes the early phases in the development of the simulation tool and the second one the actual simulation tool that has been implemented. The tool has not been completed at the time of the publication, but it has not been possible to find more recent articles on the subject. Both articles are interesting because the scopes are the same as for this project, that is developing a simulation model which can be used to analyze robustness, delay propagation etc. for a railway network. The simulation model in the articles are developed for the entire Dutch railway network, which is much larger than the network dealt with in this project. The articles have been very useful in gaining knowledge about simulation of railways.

The third article is an overview of concepts and explains general terms within the field of simulation, but does not go into further details about modelling, limitations etc. It also describes the general phases in a simulation project. It does not include any problem cases or evaluation of specific simulation tools. Therefore it is used as a basic article to get an understanding of the idea of simulation in general.

11.2 Literature on reliability

Ex ante heuristic measures of schedule reliability

In the article [3] Carey describes different heuristic measures of stability. The reason for using these measures is that analytical methods are practical only for simple system, and simulation methods are very time consuming, so in practice the most widely used measures are heuristic.

The author choose to focus on measures which can be used in advance for example in the design phase or to estimate the reliability of a proposed schedule. In practice the percentage of services which are on time, and the percentage which is more than 5 or 10 minutes late, is often used as a measure of reliability. These percentages are obtained from the frequency of the distribution of the lateness, therefore they cannot be used as a measure in advance. It should be noted that even though the measures in the article are meant to be used in advance some past information is needed to determine the distribution of the occurrence of delays.

In practice most train conflicts only involve two consecutive trains, so to minimize secondary delays slack time is usually build into the schedule. Initially the author states a measure of reliability which assumes that no secondary delays occur, except secondary delays caused by immediately proceeding trains. This measure is based on the probability of the occurrence of secondary delays, and it is a measure of the probability that a train keeps within its headway. The measure is also used as a base to formulate another measure which take all kinds of secondary delays into account.

The author also proposes measures of reliability of an entire schedule. These measures are based on the mean of the individual train reliabilities. As a second type of measures the author proposes a number of measures which build on the expected size of the secondary delays, instead of on the probability of occurrence of secondary delays. Again there is a measure for the expected secondary delays on a single train, and also a measure of reliability for a whole schedule. Both cases of measures of reliability are expected to be reasonably good when the stations in the system are not very congested. If heavily congested the measure based on the expected size of the secondary delays is likely to be best since it takes into account what happens when trains are delayed more than their scheduled headways. Also the definition of reliability implies that the reliability always increase with headways. Finally making headways more equal for all trains, reduce the probability of secondary delays.

Furthermore the author states some heuristic measures of reliability which do not use probabilities. These measures are not based on information on the previous occurrence of delays. There are several reasons for preferring these measures over the probabilistic ones e.g. what matters to the decision maker is not past delays, but future delays. All of these measures are based on the number, size and spread of minimum headways.

Finally the author plans to test the different measures by comparing the results with results obtained by using stochastic simulation.

Testing schedule performance and reliability for train stations

In this article [4] Carey and Carville develop a number of experiments with a simulation model to predict the probability distribution of secondary delays at stations. The purpose is to create a method that can be used to test and compare reliability of different proposed schedules or schedule changes.

The authors state that all methods developed so far are deterministic models, meaning that the methods do not indicate how the created schedule will perform when faced with delays. Delays are common in connection with train scheduling due to e.g. delays in passengers boarding or alighting. These primary delays cannot be eliminated. Therefore the authors are concerned with developing a method for describing the behaviour of a train schedule when faced with typical primary delays. This can be used to find a reliable schedule where primary delays cause the least secondary delays.

The authors describe a number of different experiments. First four experiments are described where delays are drawn from a uniform distribution and then the same four experiments are presented where the delays are drawn from a beta distribution. In the first experiments they simulate how secondary delays vary as the range of primary delays increase and decrease, while holding the number of trains with primary delays fixed. In the second type of experiments the authors simulate how secondary delays vary as the percentage of trains having primary delays vary.

In the first experiment the authors investigate the distribution of secondary delays and total number of delays. They display a number of curves that illustrate the behaviour of percentage of delayed trains as a function of the minutes of delays. They also calculate the mean of the delays occurring and state the confidence intervals. They find that the distribution of the means is approximately normal.

In the second experiment they investigate punctuality improvements at a station. One of the experiments is how it affects the punctuality if trains that are late are allowed to depart after a minimum required dwell time. This turns out to have a great positive effect on punctuality. Also the departure delays can be reduced compared to the arrival delays.

In the third experiment it is examined how secondary delays vary with the size of the primary delays. It is shown that secondary delays increase as the maximum primary delays increase.

The fourth experiment research the effect of allowing platform changes on the day. It is noted that on-the-day changes in platform may cause yet further secondary delays. On the contrary it turns out that allowing platform changes in response to on-the-day lateness cause a dramatic reduction in secondary delays.

The remaining experiments in the article research schedule performance when primary delays belong to a beta distribution. The reason for this is that the probability distribution function of the beta distribution has a skewed bell shape, with a longer tail of lateness than earliness, which describes real data from delays in schedules better in practice, than the uniform distribution.

Again experiments with the distribution of secondary delays are performed. These experiments show how the numbers of primary delays affect the number and size of secondary delays.

There is also an experiment on how secondary delays vary with the percentage of trains subject to primary delays. It displays that the percentage of trains with secondary delays is almost a linear function of the percentage of trains with primary delays.

The last experiment deals with the effect of allowing on-the-day platform changes. As for the experiments with the uniform distribution this turns out to have a large positive effect on reducing the secondary delays.

The simulations in this article can be used for many purposes. First from the distributions of delays the measures of punctuality can be read directly. The simulations are also useful for identifying reliability problems and bottlenecks in the system. This can be done by breaking down the delay distributions for each train service, station, platform, line, train type etc. The simulation model can also be used to estimate the effect on punctuality of proposed changes in infrastructure.

We find the article very relevant in this context because the purpose of the simulation resembles the objective of this project. The experiments and results are also very interesting.

Reliability and heterogeneity of railway services

Vromans, Dekker and Kroon [23] present the concepts of reliability in connection with public railway systems. Reliability is a key factor in transportation to preserve a high customer service level. In railway services there are many possible causes for disturbances and therefore also many causes for delays to spread in the system. One way of increasing reliability is to reduce the propagation of delays due to the interdependence between trains. The shared use of infrastructure by different railway services, different trains with different speeds and destinations is assumed to be the main reason for the propagation of delays throughout the network. In the article the authors try to overcome the problem by creating more homogeneous timetables, and thereby reduce the running time differences per track section.

The article aims at developing timetables which both absorb primary delays fast and cause as few secondary delays as possible.

The line plan and the timetable determine the heterogeneity of the railway system. In the article heterogeneity is measured as the average headway at a location along the line or between trains. Reliability in general is most often measured by the percentage of punctuality. This measure is calculated as the percentage of trains arriving within a certain number of minutes from the scheduled arrival time.

Railway traffic is considered to be homogeneous if all trains have similar characteristics, especially the same average speed. If there are large differences in the timetable characteristics of the trains using the same track then the railway traffic is called heterogeneous. Heterogeneity usually leads to small headways, which may increase delay propagation in the system. The authors propose a number of possibilities for homogenization of a railway system: Reducing speed for fast trains, Speeding up slow trains, equalizing the number of stops etc.

The article presents both a theoretical and a practical case. In the cases the current heterogeneous situation is compared to an alternative homogeneous situation, where the lines and number of stops are homogenized as much as possible. The authors use simulation to analyze and evaluate the alternative timetables. It turns out for both cases that in the homogeneous situation the reliability increases significantly, meaning that the number of primary and secondary delays decrease, and hence the new timetables should be more reliable. The authors conclude that other consequences of homogenization should also be taken into concern e.g. lower customer service and flexibility. The article does not consider these consequences.

The article is very relevant in relation to robustness, since the measures mentioned can be used to determine robustness. Furthermore homogeneity in headways turns out to have a significant impact on robustness which is an important result. The results from the article have been used as an inspiration for some of the hypotheses tested in this project.

Train service reliability. A survey of methods for deriving relationships for train delays

Mattsson [15] presents a report where the possibility of deriving causal relationships for train delays are described. Several approaches for the study of primary and secondary delays are reviewed in the report. The focus is on secondary delays and especially on how the amount of secondary delays can be related to the amount of primary delays and the capacity utilization. First the author presents some theories on calculating delay. The author connect the theories about delays to capacity. Obviously a timetable becomes more robust if it contains slack or buffer time. To increase the buffer time in a timetable is the same as to reduce the capacity. The discussion about delays therefore involves the discussion about capacity utilization. If there is lack of capacity the risk for disturbances increases.

The article presents three methods for deriving relationships for train delays; analytical methods, statistical analysis and simulation approaches. In every subject the author summarize the results from earlier research of other people. This article is mostly a literature study on the subject. The conclusion is that the analytical methods and statistical analysis are mathematical demanding and not very thorough, but they do not require as much input data and computational time as the simulation methods. When using the first two methods the timetable does not have to be completely developed.

This makes the methods good strategic decision tools in the long term planning process. The simulation methods offer the most detailed representation of a railway system, and is therefore more reliable, when it comes to studying delays.

Performance evaluation of network timetables using PETER

Goverde and Odijk [8] present a new analytic tool that evaluates network performance in a deterministic setting, corresponding to the times used in timetable construction. This new tool is called PETER (Performance Evaluation of Timed Events in Railways). PETER is a stability analysis tool for periodic timetables of interconnected train networks. The evaluation of the timetables is done without use of simulation, which makes PETER more suitable for quick evaluations since simulation can be very time consuming.

The authors present a recursive algebra that calculates the departure time at a certain time period. This departure time is calculated from the scheduled departure time for the period and the actual departure time in the previous period (including possible delays). Furthermore specific network data is taken into consideration.

By analysing this algebra PETER evaluates the stability of the timetable. In the following some stability factors are mentioned and explained shortly. The minimum network cycle time is the average cycle time when minimum cycle times are used in a periodic timetable. The minimum network cycle time gives the earliest possible departure times. By using the timetable with the earliest possible departure time the earliest operation mode is given, which is the optimal operation mode according to time and cost. The actual periodic operation mode differs from the earliest by added slack time, to make the timetable more flexible. The throughput indicated the difference between the minimum cycle time and the actual cycle time. The stability margin is a network performance indicator of robustness of the train network. The article also deals with recovery time analysis and delay propagation.

PETER is used on the Dutch Intercity (IC) network of 2000-2001 containing 19 IC train lines serving 70 stations. A case study shows how PETER performs the stability analysis. There are no specific comments or figures on the performance of PETER.

11.3 Literature on timetables

Constructing Periodic Timetables using MIP - a case study from DSB S-trains

Nielsen, Hove and Clausen [17] describe a mathematical model to create timetables in DSB S-tog. The model is a mixed integer program and is implemented in GAMS and solved with CPLEX. The model is primarily used for generating alternatives to the current timetable used at DSB S-tog, to perform scenario analysis and to consider what-if scenarios.

The main objective in the construction of timetables is to minimize the total number of trains necessary to run the resulting timetable. This objective can be achieved by merging lines. In the article the authors start by explaining all the variables and parameters used in the model such as running times, minimum turn around times and number of trains available. They also describe how the model is constructed and how feasible solutions are generated. It is described how even headways should be emphasized in the solution to improve customer service and at the same time driving times should be minimized. It is noted that there is a trade off between even headways and minimizing driving times, since a perfect even headway distribution can be achieved by converting all express lines to slow lines by introducing slack (which of course ruins the minimization of driving times).

In the second part of the article the authors investigate 2 different cases. The first one is a scenario that considers the savings of trains obtained by merging lines at the terminals. The authors state that the model is able to find optimal merges between pairs of lines given a small set of possible merges.

Next the authors consider different scenarios on the values of the parameters used for conflict checking. The scenarios show that the cost (number of trains) is heavily dependent on the infrastructure, meaning that the minimal headways defined by the infrastructure determine the cycle time and thereby the number of trains necessary to run the plan.

The model turns out to be relatively fast and solves the problem within a couple of minutes. Therefore it is convenient for what-if analysis.

Naturally this article is very interesting for this project, since it describes issues which are important in relation to developing timetables for DSB S-tog. Furthermore the MIP model described can be used to generate timetables for the simulation model developed in this project.

Analysing stability and investment in railway networks using advanced evolutionary algorithms

Engelhardt-Funke and Kolonko [6] present a genetic approach for optimizing timetables. The stability of timetables are analysed. A given timetable T is evaluated with respect to three cost functions; the total investment required $C(T)$, the total scheduled waiting time $W(T)$ and the mean actual total waiting time $V(T)$ for timetable T. A timetable is stable if $W(T) \sim V(T)$. One of the goals in the paper is to find *Pareto-optimal* timetables, which means that for a timetable T, another timetable T' does not exist such that $W(T') < W(T)$ and $C(T') < C(T)$. Given a timetable and the specifications of a network the authors presents formulas for $W(T)$, $C(T)$ and $V(T)$, and thereby show how to find Pareto-optimal timetables. A Pareto-optimal timetable is not optimal according to robustness, but optimal according to cost ($C(T)$) and passenger satisfaction ($W(T)$).

Finally a genetic approach is presented. The genetic algorithm applies to a population of timetables. In each generation the population is enlarged by offspring, which are produced from the present population using genetic operators such as cross-over and mutation. Selection of timetables for the next generation is based on the cost functions $C(T)$ and the scheduled waiting time function $W(T)$. This would develop solutions with low investment cost and low waiting times. The authors use simulated annealing to make an intensive local improvement of the population. This means that at some points a single timetable is picked random from the population and improved. This improvement will affect the entire population. This procedure speeds up the optimisation process in the genetic algorithm.

The test of the cost functions and the genetic algorithm is based on data from the German railway system.

This article does not discuss robustness in timetables directly, but it documents a way of creating timetables and gives an impression of other important factors when creating a timetable; investment cost and passenger waiting time.

11.4 Literature on recovery

Dynamic re-scheduling of trains after disruption

The authors Goodman and Takagi [7] have written an article about scheduling and recovery strategies. The paper reviews some of the applications of computers to the problem of recovering from disturbances. When recovering from disruptions different criteria are considered; regaining the scheduled departures as quickly as possible, aiming for regular headways or maximizing capacity utilization. The authors says that in metro systems the recovery strategy of gaining regular headways is often more effective that regaining the original schedule. The authors also mention different network types, such as metro and national networks. These different types of network requires different recovery strategies. Two main methods of implementing recovery strategies are discussed. One where a known set of rules is used to recover when disturbances occur, which requires complex 'rule books'. The other method is based on developing an objective function and a search procedure and iteratively finding the optimal recovery strategy. This last method requires extensive information about the network. Often these two methods are combined.

Furthermore the difference of computer decided or train operator decided recovery is discussed. The article ends with a literature review on scheduling and recovery strategies. Generally it is more complex to re-schedule than schedule, and therefore it is important to develop a robust schedule in order to avoid too much re-scheduling.

A train Holding Model for Urban Rail Transit Systems

The article by Puong and Wilson [19] describes the development of and experiments with a train holding model. The goal of using the model is to limit the negative impacts smaller disturbances have on a train network. A train holding occurs if disturbances affect a train and several other trains following and causes a temporary blockage in the network.

The holding model in the article is formulated as a Mixed Integer Problem (MIP). The objective in the model is to minimize the total passenger waiting time at stations and to minimize extra passenger riding time due to a train holding. The objective function is minimized with respect to some constraint concerning track capacity behind and ahead of the blockage causing the holding, minimum safe headways, maximum deviation from schedule and queuing situations.

The MIP is solved with a two-step procedure, starting with finding a worst case but feasible solution and then improving this solution. This two-step technique makes the execution time fast enough to solve problems in real time.

Two experiments are examined with the holding model developed. A 20 minute blockage during peak hours on a train series with 12 stations is considered. The two experiments are without and with concern of train capacity respectively. In the first experiment the holding pattern results in nearly perfectly even headways. This experiment states that passenger waiting times at stations are minimized when the variance of headways is minimized. The second experiment where train capacity is considered shows that holding trains on early stations can benefit the holding cost on later stations. It is also stated that buffer time at terminal stations (end stations) has a positive effect on secondary delays in the reverse direction.

Finally the authors discuss how the developed holding model can be used if larger disruptions occur. The model can also be used in short-turning. Short-turning occurs when the transit system is blocked and the network is separated into two parts.

We find this article interesting, mostly because is documents that buffer time at end stations and even headways have a positive effect in the reduction of secondary delays. These two subjects will also be examined in our experiments. Because the model described in the article handles smaller and bigger disturbances and because it has a reasonable execution time, it is useful in a train network, where smaller blockages occur frequently and should be eliminated fast.

Future framework for Maglev train traffic control system utilizing autonomous decentralized architecture

Kawakami [11] presents a future framework for the Maglev (magnetically levitated) trains. In Japan a superconducting Maglev train system is under development. The trains are high speed trains running between Tokyo and Osaka at 500 km/h. The goal of the system is to be able to recover from disruptions and provide electrical energy savings. The author present different recovery strategies. If small delay occurs the speed of the delayed train is raised, and the delay is eliminated. If trains are severely disrupted, the order of arrival, departure and shunting are changed if possible. The delay recovery in the system is supposed to be automated. The system calculates the minimum headway. If disruptions occur, changes are made where the headways are not at the minimum.

No computational results are given in the article, because the system is still under development.

11.5 Literature on circulation of rolling stock

Allocation of railway rolling stock for passenger trains

Abbink, Von Der Berg, Kroon and Salomon [1] consider the problem of minimizing the number of train units of different types and subtypes for an hourly train series in the Netherlands, given that the passengers seat demand must be satisfied. The authors point to the fact that for a railway company to have a high service level for the passengers, it requires high punctuality for the trains and an adequate rolling stock capacity. Since rolling stock capacity is currently limited in the Dutch railways, this article seeks to find a more effective allocation of the available rolling stock.

The planning process related to rolling stock allocation and circulation starts after the line system and the timetables have been generated. When determining the allocation of equipment the preferred equipment must be taken into account as much as possible. Also the allocation is determined by the required capacity, which is again determined from an expected number of passengers. Another restriction is that the length of a train cannot exceed the length of the shortest platform along the route. Furthermore at most one train type can be allocated for each train, because train units of different types cannot be combined into one train. Finally it is desirable to have as few subtypes as possible, since this may increase the robustness of the railway system because adjustment of traffic control becomes simpler.

The article presents a model for allocating different material types of rolling stock to different train series in the best possible way. The authors present an integer programming (IP) model that minimizes the total number of seat shortages on the trains during the morning rush hour. This is done by allocating material types and possibly subtypes with different capacities to all trains running simultaneously at 8 o'clock, which is the busiest moment of the day.

The approach is applied to the Dutch railways for several scenarios that differ in the number of material types and subtypes that can be allocated to a line. The model is also tested on 50 regional train series (which is almost the entire set of regional train series in the Netherlands) and proved to find an optimal solution in a couple of seconds using CPLEX. Finally it is concluded that the shortages in the number of seats in the solution found by the model was significantly lower than in the manual solution currently being used. Also the model reduced the throughput time of the entire planning process, which gives the possibility of analyzing several scenarios and compare these.

Efficient circulation of rolling stock

Alfieri, Groot, Kroon and Schrijver [2] describe a model to determine the circulation of rolling stock on a single line for a single day. The objective is to find an optimal match between customer demand and rolling stock capacity. In order to utilize the train units on the line in an efficient way, the units are added to or removed from the trains in certain stations according to the customer demand. Adding or removing train has to follow specific rules, so it is important to keep track of the order of units in the trains. These rules make the circulation of rolling stock a very complex problem. Finding an appropriate rolling stock circulation means finding a balance between several objectives such as minimizing the number of train units required for operating the train lines and minimizing the variable rolling stock cost. In the article several objectives are explored, to find the best solution. The different objectives concern minimizing the number of trains, the number of kilometres driven or a combination of these. The allocation problem is solved with and without concern of the composition of the trains.

The approach in this article is to model the problem as an IP formulation. The model is used for a single train series connecting two end stations, and the timetables are fixed. The number of trains running depends on the circulation time for the train series and the frequency. This type of problem is modelled as an ordered multi-commodity flow problem in the article, since the order of the train units in the trains are important. The model is represented in a flow graph where the nodes correspond to the events and edges correspond to trips. In each node flow balance must be assured. The model is also based on describing the feasible transitions of the compositions of the trains in a number of transition graphs. In these graphs nodes represent feasible train compositions on a trip and edges represent feasible transitions between compositions. The aim is to find an appropriate path in each transition graph and at the same time to keep track of the stock of the train units in all stations.

The paper deals with the solution approach based on a combination of solving a multi-commodity flow problem and finding paths in the transition graphs. Because the dimension of the problem becomes very large the solution approach is partitioned into a flow part and a composition part. The flow part deals with solving the integer multi-commodity flow problem and provides a lower bound since the composition is neglected. Then it is checked whether the given solution can be transformed into an overall feasible solution to the problem, with regards to transitions, without changing the objective value.

The algorithm is tested on real-life case studies from the Dutch railway company. The results show that most of the computational time is spend on solving the flow problem. The results also show that the algorithm is capable of solving the problem to optimality within reasonable computational times. It is also concluded that in order to study more complex cases e.g. several trains or lines, different methods would be needed, since the problem might become too large for this solution approach.

Circulation of railway rolling stock: A branch-and-price approach

Peeters and Kroon [18] describe an algorithmic approach to determine an efficient railway rolling stock circulation on a single line or on a set of interacting lines. The problem of allocation of rolling stock, in this article, is the problem of satisfying passenger seat demand at minimum cost.

The authors have developed a model for solving the allocation of rolling stock material. The model deals with passenger demand, different types of trains, shunting of trains and inventory position at the stations. The model also take into consideration the composition of the trains, since this is an important issue when recombining the train units. The composition of the trains helps to make a better match between available rolling stock and the passenger seat demand. For each train the possible changes in its composition at a station can be presented by a transition graph, where the nodes represent the feasible compositions on a trip and the arcs represent the feasible transitions between compositions at a station. The objective of the model minimizes shunting operations, carriage kilometers and kilometer shortages. These three factors are combined in one cost function in the objective function.

Dantzig-Wolfe decomposition is used to decompose the problem, where the decomposition is based on the trains. A linear programming (LP) relaxation of the decomposed problem is solved using column generation. The solution to the LP-relaxed problem results in a price, which is the shortest path through the transition graph for a train. To obtain a proven optimal integer solution the authors develop a branch-and-price procedure, where the price is calculated as just explained and branching is done on the composition of the trains.

The branch-and-price algorithm is tested on real-life instances from the Dutch operator of passenger trains, which means that the decomposed problem has a subproblem for each train. The required CPU time is short compared to using CPLEX, which makes the method useful for performing what-if analysis. The article presents some what-if analysis, e.g. the investigation of only using two types of trains on a line. Another example is the question of extending a platform at a single station and thereby the maximum length of the trains going through this station. This means that the model can be used by planners to solve many subproblems in the planing process.

11.6 Literature on shunting

Shunting of passenger train units: An integrated approach

Schrijver, Lentink and Kroon [21] describe a new model for the Train Unit Shunting Problem (TUSP). Usually extra rolling stock is available outside the rush hour. This extra rolling stock can be parked at a shunting yard in order to be able to fully use the railway infrastructure for other trains. Shunting yards are also used at night as depots for the trains. The order in which the trains are parked at the shunting yard is not without importance. When a train unit is to be used from the shunting yard it should be reachable and at night the trains should be parked in the order they are to be used the next day. The shunting plans created should be robust, since changes almost always occur. The train unit shunting problem consists of matching arrival and departure of shunting units and parking these shunting units in the shunting yard such that the total shunting cost is minimized.

The authors split the problem in two case; a basic model where shunting is only possible from one side, meaning there is no passing through the shunting yard, and an extended model where shunting is possible from both sides. In both model the objective is to minimize splitting of trains because this results in more shunting and to avoid parking trains of different types at the same shunting track.

Results are based on real-life cases of the Dutch passenger railway operator. The article does not present any actual computational results.

Applying Operations Research techniques to planning of train shunting

In the paper [13] Lentink, Fioole, Kroon and Van't Woudt present a model based algorithmic solution approach for creating shunt plans in a railway station. Creating such plans includes matching of arriving and departing train units, decisions on where to park the shunted units and determining the routes for the shunted units in the station.

Because practical situations often involve many train units, the problem becomes too large to be solved as one optimization problem. So the proposed solution approach consists of a decomposition of the problem into 4 subproblems:

1. Matching arriving and departing train units
2. Estimating route costs of train units

3. Parking of train units on shunting tracks

4. Routing of train units to shunting yards

These 4 subproblems are solved separately. The first subproblem is solved as a network problem, and seeks to keep as many train units together to minimize the number of shuntings. The second subproblem is solved by estimating the cost of routing for all possible routes in the network from subproblem 1. The third problem is solved as a set partitioning problem, assigning units to shunt tracks. The set partitioning problem is solved using column generation. The fourth subproblem is solved using a search algorithm to search for feasible routes sequentially.

Finally the article presents two experiments, for two stations in the Dutch railway network. The results show that the algorithm is able to park all blocks of train units in 7 out of 8 cases, within reasonable computational time.

12 Planning at DSB S-tog

In this section the planning process and construction of timetables at DSB S-tog will be described. Because the network is considered fixed only the 3 blocks of train series planning, time tabling and rolling stock planning, in Figure 5 in chapter 7 concerning planning in general, are considered in the planning process at DSB S-tog. The first step in the planning process is to determine the stopping patterns of the lines. The stopping patterns are constructed from expected passenger numbers. In planning of the stopping patterns and the departure times in the timetable it is also considered important to allocate the lines as evenly as possible, with regards to planned headways, to ensure the best buffer times between trains, e.g. if there are 10 lines they should be planned with headways of 2 minutes in the central section of the network. This is not always completely possible, due to the running times elsewhere in the network. In the next step the minimum driving times between the stations are calculated based on the shape of the tracks and the maximal speed of the trains. Given the timetables the necessary amount of rolling stock and crew is determined, and at last the final plan is chosen. The planning process at DSB S-tog is presented as a flow diagram in Figure 7.

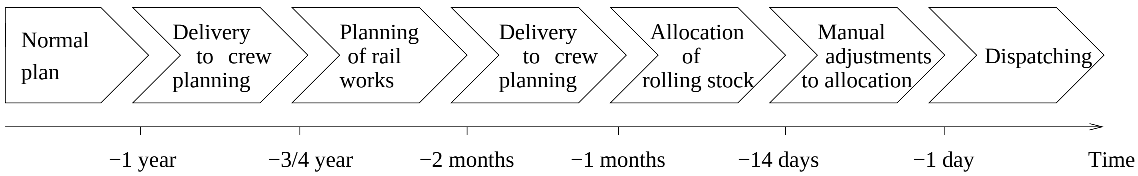


Figure 7: The planning process at S-tog

Every year an adjusted normal plan is generated. A normal plan includes timetables with running/dwell times and departure/arrival times. The normal plan also includes a circulation plan for the rolling stock. The department of material planning, called MAS, allocates the rolling stock after the timetable has been generated. The customer demand is used in the planning of rolling stock circulation to determine the size of the train sets. When the normal plan has been developed, crew scheduling is performed.

The next phase in Figure 7 is adjustment of the plan according to the planning of rail maintenance work. Since DSB S-tog has scheduled rail maintenance work in some parts of the system almost all year long, a part of the planning process is to adjust the normal plan and crew schedule according to rail works. In 2004 the normal plan was used for only 15 days during the last 6 months. After the known rail works are scheduled the crew planning begins. One month before dispatching specific trains are allocated to the rolling stock circulation plan. 14 days before dispatching the last adjustments to the plan are made. At last the plan is ready for dispatching after a year of planning.

12.1 Design of timetables at DSB S-tog

Timetabling is done by the department of production planning called PPA. DSB S-tog has a mathematical model which can be used for generating timetables, see [17]. The problem is formulated as a mixed integer problem (MIP). The MIP model is implemented in GAMS and solved by the MIP solver in CPLEX. The cost of operating a given timetable is proportional to the number of trains required to run the plan. Therefore the main objective in the MIP model is to minimize the number of train sets necessary. An additional objective is to minimize the time between departures at certain stations e.g. København, in cases where several lines cover the same series. The inputs to the model are the defined train series network, the stopping pattern for each line, the running times between the stations, the dwell time at stations, a requirement of 20 minute frequencies on all lines and scheduled headways of 2 minutes in the central section. The model does not take customer demand into account. The main decision variables in the model are the departure times from each station for each line. The output from the model is a timetable.

To make the timetable robust against disturbances, slack time is incorporated. Dwell times are adapted to the expected number of passengers and disruption patterns at each station. Running times are increased with a buffer of approximately 3.6 seconds pr. kilometre in certain places in the network. Also at the end stations slack is added to minimize the risk of new trips being affected by the lateness from the subsequent trips.

13 Circulation of rolling stock at DSB S-tog

In this chapter circulation of rolling stock at DSB S-tog will be described.

13.1 Rolling stock at DSB S-tog

DSB S-tog use 3 different types of trains called 2nd, 3rd and 4th generation, where the 4th generation trains are the newest. In Table 1 the 2003 numbers of the 3 different train types are seen. In 2005 lines A and E between Køge or Hundige and Hillerød are covered by the new fourth generation trains, because this series has been improved to be able to handle the speed of this train type. Lines B, C and H can be covered by all three types of trains. Ringbanen, line F, is always covered by the third generation trains. In 2006 all the S-train lines should be covered by 4th generation trains. It is not possible to make any combination of the trains across the three different generations. The S-trains are powered by electricity.

Type	Number of trains	Set type
2nd generation	5	2-coach
	61	4-coach
3rd generation	8	4-coach train sets
4th generation	83	8-coach train sets

Table 1: S-trains rolling stock at the end of 2003

There are several different material depots, where trains can be stored or shunting can occur. These depots are at København, Høje Taastrup, Køge, Hillerød, Hundige, Farum, Frederikssund, Klampenborg and Ballerup.

Maintenance of the trains can only be done at Høje Taastrup station, so all the trains have to terminate at this station within given intervals to get a service inspection. A train can normally drive 22.000 kilometres or approximately 60 days before a maintenance check is needed. The only prepare centre is in Hundige, where external cleaning of the trains is carried out. Internal cleaning can be handled at most of the large stations.

13.2 Circulation plan

After the timetable is constructed the allocation of rolling stock is scheduled. First it is planned how many train units and which types are needed for each line but not exactly which specific train units. The lengths of the trains are determined from the customer demand, but the maximum length of a train is limited by the shortest platform in the network. The plan for the circulation of rolling stock indicates how many train units of each type are needed on a specific line on a specific day.

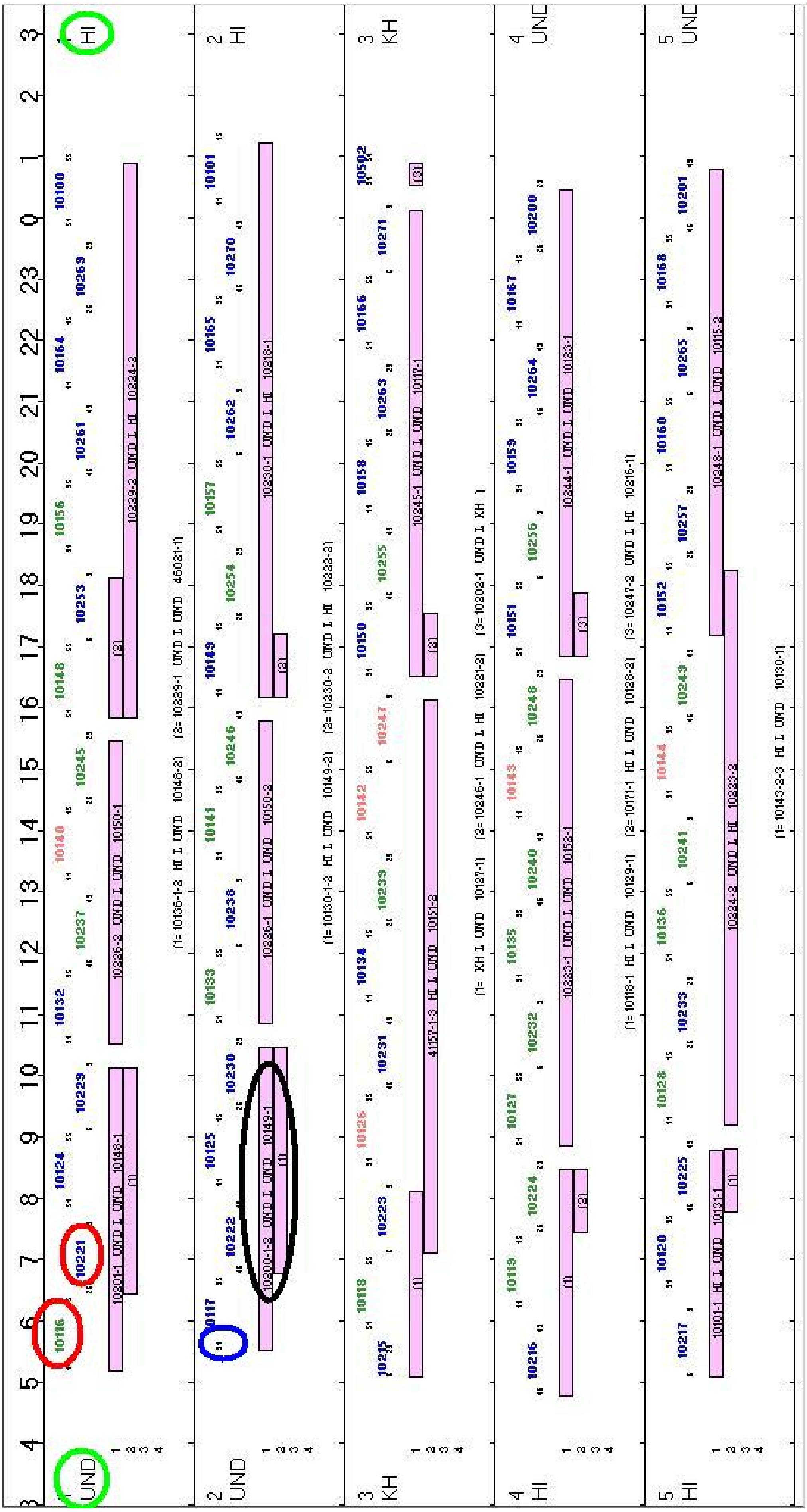


Figure 8: Rolling stock circulation plan for line A

The plan for the circulation of the rolling stock only specifies that a train is needed on a specific line, but not what specific train units to use. The specific allocation of the train units is taken care of later in the process. A plan for the circulation of the rolling stock on a specific line contains a number of trains as shown in Figure 8. The figure shows five out of eight trains from a plan for the circulation of the rolling stock for the line A on a weekday. In a train a five digit trip number $xxxyy$ (the red circles in Figure 8) indicates exactly where the train is going and when it is going through København. For example the trip number $xxxyy = 10116$ represents a trip on the A line. The trip number is divided into the first three digits $xxx = 101$ and the last two digits $yy = 16$. The first three digits 101 indicates an A line train because A line trains are represented by the numbers 100-149. When it is an odd number e.g. 101 it is an A line train going north, even numbers indicate a trip going south. The last two digits 16 indicate exactly what A line train during the day this trip represents. Every train line is scheduled with a frequency of three trains per hour (leaving every 20 minutes). Main lines and extra lines, e.g. B and B^+, are run with a 10 minute interval. The trip number indicates the hour of the day and whether it is the first, second or third train in that hour. This is determined by using modulus calculation on the last to digits. Because the frequency is three trains per hour the modulus coefficient is 3. The remainder indicates whether it is the first, second or the third train. The quotient indicates the hour the train is going through København. The remainder is either 0, 1 or 2, if it is 0 it is the first train and so on.

Again as an example the trip number $xxxyy = 10116$ is an A line train going north to Hillerød, and it is the second A line train going through København in the fifth hour. 16 represents the fifth hour and the second train, because $16 = 3 \times \mathbf{5} + \mathbf{1}$. Another example is the trip number 10221, which is an A line train going south because 102 is an even number. It is the first train in the seventh hour, because $21 = 3 \times \mathbf{7} + \mathbf{0}$.

The small two-digit numbers written below the trip numbers in the plan (the blue circle in Figure 8) are the minutes of respectively departure and arrival from the end station. The capital letters at the beginning and the end of each train unit, e.g. UND (Hundige) and HI (Hillerød) (the green circles in figure 8) indicate where the train starts in the morning and ends in the evening. The second train departs from Hundige at 5:31 and arrives at Hillerød at 6:35. The hour is seen in the top of the figure. Figure 8 only shows five out of eighth trains needed to cover line A. The number of trains needed depend on the cycle time of the entire line (e.g. the Hillerød-Hundige-Hillerød) and the frequency of the trains on the line. The cycle time of the line divided by the frequency gives the number of trains. The cycle time between Hillerød-Hundige-Hillerød is $63+22+64+11 = 160$ minutes including waiting time at the end stations (63 minutes from Hillerød to Hundige, 22 minutes of waiting in Hundige, 64 minutes from Hundige to Hillerød and 11 minutes of waiting in Hillerød. These numbers are calculated from the arrival and departure times in the production plan). The interval between two successive S-trains covering the same line is always 20 minutes. This gives a number of $160/20 = 8$ trains needed to cover line A.

The boxes in the plan indicate the train units. The color of the box depends on the train type. The trains used in the production plan in Figure 8 are 4th generation trains. This is indicated by using pink boxes. If there are two boxes the train is of double length (2 train units). Double length trains are usually used during rush hour. As an example the first train is of double length in the time interval between 6:26 and 10:09. A new box indicates that a change to a different train covering the line is planned. The rush hour ends at around 10 o'clock according to this plan and afterwards the trains are usually shortened. Sometimes instead of shortening the train, which can be very time consuming, a new train is inserted e.g. as is the case for the first train in the production plan in Figure 8. The text in the boxes (the black circle in Figure 8) says where the trains have been used before and where they are to be used next.

A plan for the circulation of rolling stock like the one for line A shown in Figure 8 is made for all the lines A, B, C, E, F and H, as well as for the x- and the +-lines. In some cases these extra lines (x and +) are shown in the same circulation plan as the main line, this is the case with line B and B^+ which are represented in the same plan. This is done to simplify the planning process, because the trains may switch line during the circulation to reduce waiting time at the end stations. The process of switching between lines is called merging. For example the B-train arrives at Høje Taastrup station at the 0th minute according to the timetable. The same B-train cannot be ready to leave again in the 0th minute as the timetable indicates. Instead of waiting 20 minutes for the next departure for the B-train it leaves in the 10th minute as a B^+-train. This reduces the waiting time at the end stations and thereby the total number of trains. Figure 9 and 10 illustrates this merging process.

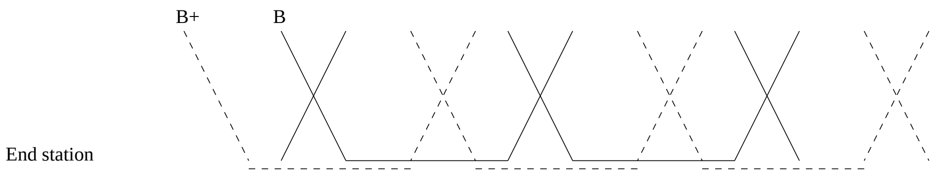


Figure 9: Line B and B^+

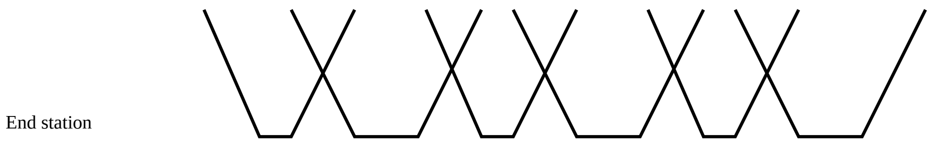


Figure 10: Merging of line B and B^+

Allocation of rolling stock is partly done automatically at DSB S-tog. A model is used where the objectives are one or more of the following:

- Minimize the number of trains used
- Minimize the number of kilometres driven
- Minimize the number of passengers not able to get a seat
- Maximize reserve

- Maximize seats.

This model is used to optimize the rolling stock used in the rush hour. The model is also used to examine the requirement for rolling stock and in some of the phases of allocation of rolling stock combined with manual scheduling work.

As mentioned in chapter 12 new circulation plans are created when the timetable is improved once a year. The circulation planners make these plans in a specified program, where they build up the plan by hand using drag and drop. It is made from experience and the changes in the timetable are often small, which enables the planners to reuse some sequences of the old plans. The circulation plans also include periodic maintenance of the trains. About 2 months before the new timetable is published actual train sets are attached to the rolling stock plan. This is mostly done automatically. As a main rule the same trains run the same lines day after day, this minimizes dead heading of the trains (transport without passengers). During the next period after the circulation plan has been completed, the situation is monitored to adjust the new timetable, if any changes occur because of acute track maintenance or severe disturbances.

When the new timetable is published and running, the network is monitored from a control centre, and different recovery strategies are used if and when disturbances occur. This phase is examined in chapter 15.

14 Disturbances at DSB- S-tog

In the following section regularity and reliability will be introduced. In the next section the causes of disturbances and delays for DSB S-tog will be described.

14.1 Regularity and reliability

In connection with recovery of the system when disturbances occur, a measure is needed to determine the condition of the system. Regularity can be used as such a measure, because it indicates the percentage of departures on time. The regularity can also be used to e.g. determine when to take action to recover the system or when to re-insert cancelled lines once the system has been recovered. Regularity is calculated as

$$1 - \frac{\text{Number of late departures}}{\text{Number of departures in total}}$$

DSB S-tog use regularity as a measure to determine when disturbances have occurred in the network. Whenever the regularity is above 95% the system is considered stable i.e. there are no disturbances. If the regularity descends below the regularity limit of 95% this is an indication of disturbances in the system and it should be considered whether or not to take action to recover the system. At DSB S-tog there is no lower limit on the regularity that indicates the time to begin recovering, this is a decision that is being made individually by the controller every time a situation occurs.

In connection with the recovery of the system an additional measure can be used to determine the effect on the customer service as a consequence of the number of trains affected by the recovery e.g. if lines are cancelled to recover the system this results in a lower level of customer service. Naturally the fewer trains in the system, the higher possible regularity, but to measure the effect on customer service level, reliability is introduced. In this context reliability measures the number of actual departures from the stations compared to the scheduled number of departures.

$$\frac{\text{Number of actual departures}}{\text{Number of scheduled departures}}$$

14.2 Causes of disturbances at DSB- S-tog

The most important causes of disturbances for DSB S-tog in 2004 were

- A broken overhead wire between Sydhavn and Dybbølsbro stations during morning rush hour in January
- Weather e.g. heavy rain in August and a stroke of lightning i September
- Track maintenance work
- Delays in passengers boarding or alighting.

More than 2.5 minutes lateness for a train is defined as a delay at DSB S-tog and must be reported. When a train is late for arrival at a station, a code for the cause of the delay is registered. These codes are used to improve the regularity in the different areas of causes of disturbances.

Generally most irregularities occur at Nørreport station, because it is one of the busiest stations. Nørreport is not very big according to passenger capacity and the passengers can connect with both busses, the Metro and the national trains at this station. These factors increase the risk of irregularities.

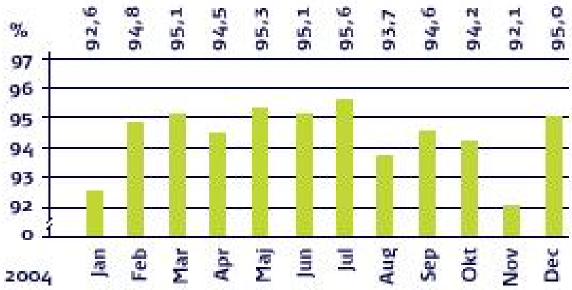


Figure 11: Regularity in 2004

Factor	Percentage of disturbances
DSB S-trains	47%
Infrastructure	44%
External factors	9%

Table 2: Factors affecting S-trains in 2004

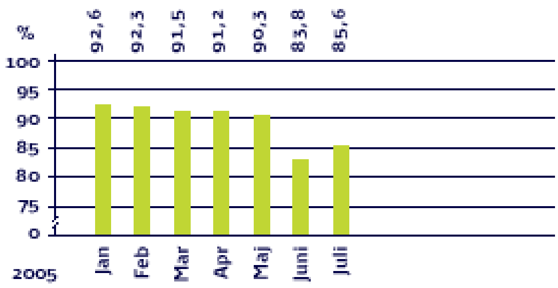


Figure 12: Regularity in the first 7 months of 2005

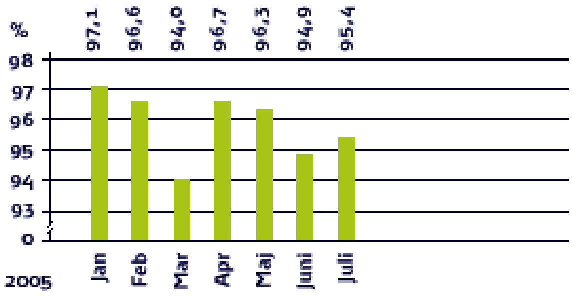


Figure 13: Reliability in the first 7 months of 2005

As mentioned DSB S-tog has a target of achieving a regularity rate of 95%. In 2007 the aim is for a regularity rate of 97%. DSB S-tog achieved an average regularity rate of 94,4% in 2004, which is below the target, although it is an improvement from previous years. The highest rate of regularity was reached in July at 95,6% and the lowest in November at 92,1%. Figure 11 shows the regularity rates for 2004. The results reveal considerable fluctuation. In January, which is a cold month, snowfall and other seasonal weather problems caused irregularities. This was also the case in 2003 where the regularity fell to 85,3% in January. Extensive track work also had a negative impact on regularity in 2004. In Table 2 the percentages of causes of disturbances are shown. As seen in the figure the largest cause of disturbances is the trains, which is a results of e.g. failures on the trains. In Figures 12 and 13 the regularity and reliability for the first 7 months of 2005 are shown. As seen in the figures the regularity is quite low compared to the target of 95%. In June and July the regularity is approximately 85% which is a results of a large number of departures being cancelled due to speed limitations because of the conditions of the tracks.

15 Recovery strategies and methods at DSB S-tog

In this chapter recovery strategies and methods used at DSB S-tog will be described. Furthermore it is explained how the recovery methods are implemented. Some of the practical requirements that need to be taken care of during recovery will also be examined.

15.1 Recovery strategies

When the S-train network is influenced by disturbances different kinds of changes are applied to the system to recover from the disruptions. When changes are made, the passengers are informed, to make sure that the disturbances affect them as little as possible. In situations with delays the controller will try to recover by re-establishing the original plan, in order to avoid affection the passengers more than necessary. If the disturbances make it impossible to re-establish the original plan, re-scheduling will have to take place.

15.1.1 Re-establishing strategies

When disturbances occur in the S-train network all planned marshalling to larger or smaller size is cancelled. This is done to use the time more effective on recovering instead of creating further delays. Also if delays have occurred, more passengers may be waiting at the station so if the train has to leave the station within the scheduled dwell time it can be an advantage if the train has already marshalled to larger size to leave it like this.

Platform changes on-the-day are being used e.g. if a train arrives late at the terminal station it might be re-scheduled to the platform where it has the next departure.

A train may skip some of the smaller stations if delays occur e.g. a B line train on the way from Hellerup to Holte may stop at Lyngby only and skip all stations in between (like the A and E line trains). In this case passengers will be advices on an earlier station, to give them the possibility of changing train.

A late train may turn around before the end station and continue in the opposite direction according to the plan. For example an A line train going to Hillerød can turn around in Holte if it is sufficiently late.

If a fast train catches up with a slower train due to delays and it is impossible for the fast train to pass the slow train, the two trains may swap 'identity' or running patterns on the next station, so the first train leaves as a fast train and the latter train becomes a slow train. As an example if an H line train catches up with a C line train on the way to Vanløse, the C line train which is in front may continue from Vanløse as an H line train, and then the H line train will continue as a C line train.

If large delays influence a specific train e.g. an A line train, a new A line train can be inserted at København to leave on the scheduled time. When the delayed A line train arrives at København it is simply taken out. The passengers in the delayed train will have to leave the train at København and take the next train. Considering that the train was already late these passengers are of course further delayed, but at the same time all other passengers planning to use the train from København can continue their travel without delays.

When trains are put out of order, so that they will have to be repaired before they can be used again, the controller tries to insert a replacement train to take over the trip whenever possible. Replacement trains are usually scheduled to begin their trip from København, since this is where both trains and crew are available in reserve.

Reducing dwell times to a minimum is possible at all the stations in the network. The train driver can decide to reduce the dwell time in order to reduce to delay. Reducing headways to a minimum is possible at some of the longer stretches of tracks, usually in the ends of the train series. Reducing running times might be possible in few sections of the network, when disturbances occur. A system exists that informs the train driver on which speed he should drive in order to keep the distance to the preceding train.

The order of the trains follows a specific sequence given by the timetable. This sequence is only broken if large delays occur. Changes in the order are not always easy. Overtaking can only take place at stations with more than one track in the same direction or at places in the network with double tracks. Only few stations have double tracks, which makes overtaking rare. If a train is delayed at arrival to a station all other trains scheduled for arrival later at the same platform are held back until the delayed train has arrived, unless the controller informs the system to react otherwise. The controllers learn by experience how much a train must be delayed before they have to take action and change the order of trains.

15.1.2 Re-scheduling strategies

When the sizes of the disturbances make it impossible to re-establish the original plan, the controller needs to re-schedule the trains.

One of the strategies that DSB S-tog use is that when large disturbances occur, the +-lines and x-lines are cancelled. This results in larger headways which may reduce delays considerably. As of today DSB S-tog never plan re-insertion of cancelled lines the same day. All recovery is done with regards to execution of normal schedule the following morning.

If disturbances block the traffic somewhere in the central section between Svanemøllen and København e.g. at Nørreport, then the train lines are divided into a northern part and a southern part that circulate between the end stations and the blocked station.

All recovery strategies are evaluated according to estimates on the capacity of free rolling stock and available personnel. Sometimes when irregularities occur there are too few train drivers to re-establish the normal schedule. This is a limitation for recovery.

15.2 Recovery implementation methods and practical requirements

At DSB S-tog the different recovery strategies and methods are not implemented in an automatic decision system. A decision about using a specific recovery method in a given situation is typically based on experience. A rule book concerning which methods to use exists but is rarely used. Plans for the future is to update this rule book and make some of the decision automatic and concerning both materiel and personnel. This new system should be able to generate solutions automatically, for restoring the normal operations plan. It should also be possible to evaluate several feasible solutions with regards to quality e.g. robustness and total recovery time in real-time.

DSB S-tog has a system that shows the original plan as it was in the morning. This can be of great help to determine where the trains are located in the system at a given time. This information is very important to the controller, when he or she needs to make a new plan or re-schedule the trains. The system can be used for manually re-scheduling the trains.

A system for generating solutions for re-inserting cancelled trains is under development. When lines are cancelled, the trains are taken out at the depots. When re-inserting the trains, crew needs to be transported to the depots. Given a train which is the first possible for transporting crew to the depots, the system can generate a solution that takes care of the order of re-insertion of the trains. The system only generates feasible solutions and does not take into consideration the quality of the solutions.

Trains running on lines that are cancelled for the rest of the day, are shunted to the shunting yards at the end stations where they are scheduled for the following morning. Defective train units are shunted to the maintenance yard in time according to the gravity of the faults, meaning that if the train is severely damaged it is taken directly to the maintenance yard, whereas if it is only a minor fault, e.g. a door that cannot open, it may continue the trip for the rest of the day.

If disturbances and delays have occurred in the system during the day, the main goal for recovering is to ensure the necessary number of train units are at each depot at the end of the day to prepare for the scheduled traffic the following morning. Sometimes less important maintenance schedules are cancelled to keep the necessary number of trains on the tracks the next day. The different defects on the trains are reported and categorized in the production plan, so the controller can use this information to cancel or postpone less crucial maintenance in the planning of recovery.

16 Arena and description of the first models

In this chapter an introduction and description of the simulation program Arena will be given. Only the elements of Arena used in the models in this project will be explained. We have learned about Arena by reading the text book [12]. To illustrate our learning process with Arena, the use of Arena will be examined through two of the models, made before the final model of the S-train network was build. Starting with a very simple model in section 16.2, where the subject of routing between two stations was explored. In Model 2 in section 16.3 three entire stations were build with concern of dwell time, delay, headways, fast routes etc. First Arena is described in general.

16.1 Arena

At the highest level of abstraction, Arena deals with entities, resources, variables, attributes and events. Entities are the elements that traverse the model during simulation e.g. the trains. Resources can represent processes and other static assets in the model e.g. stations and tracks. Variables are all the adjustable or changing parts of the model e.g. running times and dwell times. Variables are global and pertain the whole model as opposed to attributes, which are entity specific variables representing characteristics for the different entities in the model. An attribute only pertain the entity it is connected to. An example of an attribute can be the time the entity should be disposed and leave the system. This can be specific for each entity and can be stored in an attribute. If the value is used in other correlations, not only including the specific entity, the value should be stored in a variable. Finally events are all the things that happen during the run of the simulation. Variables and attributes might be changed during an event. Examples of events are arrivals and departures, or when an entity enters or leaves the model.

When building a simulation model in Arena the basic building blocks are modules. The modules are split into two categories: flowchart modules and data modules, see Figure 14 and 15.

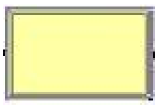


Figure 14: Flowchart Module

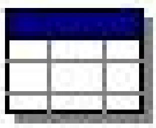


Figure 15: Data Module

Flowchart modules describe the dynamic processes, the movements and the changes in the model. The data for the flowchart modules can be specified in the associated dialog boxes. These modules are connected to indicate the movement of the entities in the model. The data modules define the characteristics of different elements like entities, queues and resources. They are also used to set variables or expressions that pertain the whole model.

At a lower level of abstraction, elements and blocks can be used instead of modules. Basic process modules often have some of the same features as elements and blocks, but not with the same level of detail. Only a few element and blocks are used to model the S-train network and will therefore not be described in further detail.

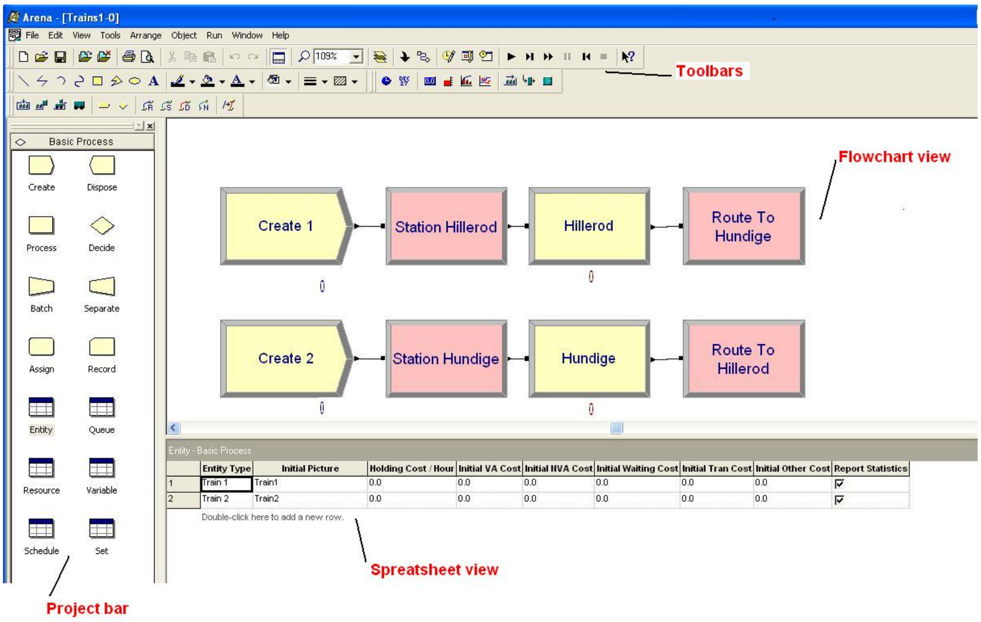
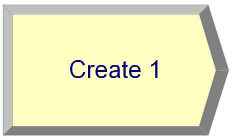


Figure 16: Arena window

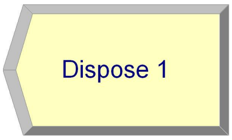
The Arena window is shown in Figure 16. At the top of the window the toolbars are placed. The toolbars can be added or removed as in other Microsoft Windows applications. In the left side of the window the project bar is placed. Here the flowchart and the data modules are found. The flowchart modules are inserted into the model by drag-and-drop. The model window is separated into the flowchart view and the spreadsheet view. In the flowchart view the building blocks in the model and the animation of the model are shown. This is the visualization of the model. The spreadsheet view shows all the data in the model. The same data, which can be seen in the dialog box by double clicking on the flowchart modules, can also be seen in the spreadsheet view, but the spreadsheet view shows all modules of the specific type at the same time. The data can be modified in the spreadsheet view or in the dialog box.

In the following the flowchart modules and some of the data module used to generate the S-train network are shown and described. The flowchart modules are separated into Process modules and Transfer modules.

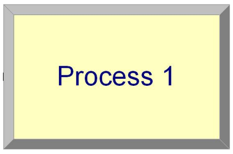
Process flowchart modules:



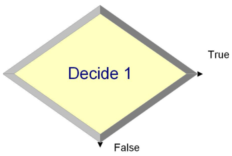
The **Create flowchart module** is intended as the starting point for entities in a simulation model. The Create module is used to insert entities in the system. It is possible to specify what entity to create/insert, how many and the time interval between the created entities.



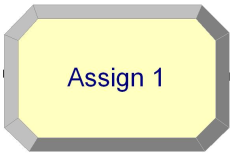
The **Dispose flowchart module** is intended as the ending point for entities in a simulation model. The dispose module removes entities from the model.



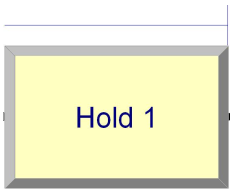
The **Process flowchart module** provides different possibilities. The entity entering the Process module is seized and can be delayed. A resource with a specific capacity can be added to the model and a queue is connected to this resource. When the job in the process is finished, the entity is released and the resource becomes idle. Instead of the Process module four separate modules can be used; a Seize module, a Delay module, a Resource module and a Release module.



The **Decide flowchart module** is used if the entities should be able to transfer different ways in the model according to some given conditions. The decide module can split in as many different directions as wanted. The different directions can either be determined by chance (e.g. 20% one way and 80% another way) or by a condition (e.g. one way if an expression is true and another way if not).

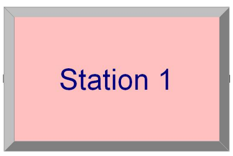


The **Assign flowchart module** assigns new values to e.g. attributes or variables. Multiple assignments can be made within a single Assign module.

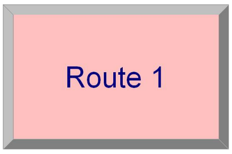


The **Hold flowchart module** will hold back an entity in a queue, while it either waits for a signal or waits for a specified condition to become true. The queue is represented by the line above the module.

Transfer flowchart modules:

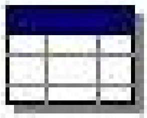


The **Station flowchart module** defines a station, where entities can be routed to. The Station module is not specific for this project but a general Arena module.

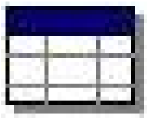


The **Route flowchart module** transfers an entity to a specified station, or the next station in the station visitation sequence defined for the entity. A delay time to transfer to the next station can be defined. If a Route module is not used, the travel time between two flowchart modules is zero.

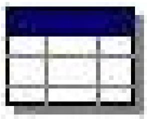
Data modules:



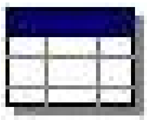
The **Entity data module** defines the various entity types and their initial picture values in a simulation. Entities can be defined in the Entity data module or a new entity will automatically be defined when used for the first time in a flowchart module. The entity pictures can be edited (see the menu Edit-Entity Picture). Various colored trains are made to match particular S-train lines in the models in this project.



The **Queue data module** may be utilized to change the ranking rule for a specified queue. The default ranking rule for all queues is first-in-first-out.



The **Variable data module** is used to define the dimension and initial value(s) of the variables. A variable can represent a single value, an array or a matrix of values. Variables can be referred to in other modules (e.g. the Decide module), can be reassigned a new value with the Assign module or can be used in any expression.



The **Advanced Set data module** specifies queue sets, entity sets and other sets and their respective members. A set defines a group of similar elements that may be referenced via a common name and a set index.

Examples of how these different modules are used are seen in the following sections. All the modules except the Route and Station modules are connected using the Connect button on the toolbar, see Figure 17. Then the entities will travel from module to module during the simulation. The travel time on the connections are zero, as mentioned Route modules are used when the travel time between two modules should not be zero.

Figure 17: Connect button

16.2 Description of Model 1

Model 1 is very simple as seen in Figure 18. The model describes how entities (trains) can be routed between stations. Four different flowchart modules are used (Create, Station, Process and Route). Some of them are linked with connections (the lines between the modules) and some are linked with routes. The objective of this model was to have trains running on time between two stations (Hillerød and Hundige) with a given running time and dwell time, with no concern of headways and possible delay. The running times between the two stations are set to 6 minutes and the dwell times at the stations are set to 2 minutes. This is a deterministic simulation model, because the running times and the dwell times are constant.

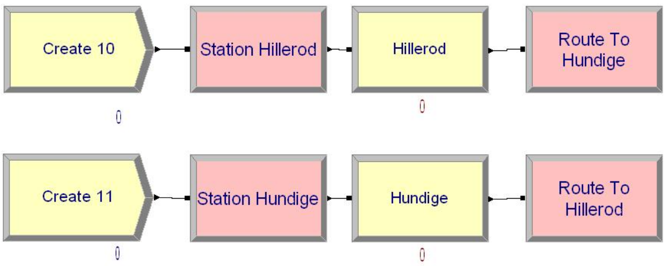


Figure 18: Model 1

The use of the four different flowchart modules, Create, Station, Process and Route, will be explained in detail. A double click on a module opens a dialog box like the one in Figure 19. The dialog box is used to specify the data for the associated module.

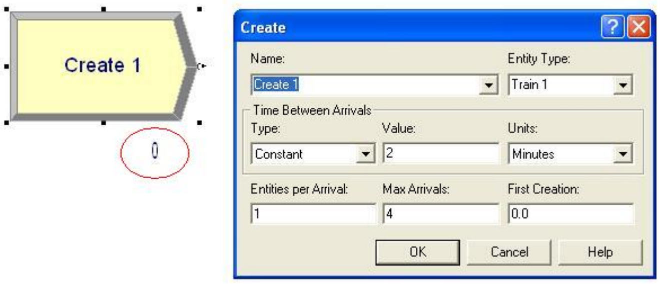


Figure 19: Create module

As explained the Create flowchart modules are where the entities (trains) enter the system. In the Create module in Figure 19 the 'Name' can be set arbitrarily, this is the name shown on the module in the model. In Model 1 the default name Create 1 is used. 'Entity Type' decides what entity to create. Entity type is chosen from the list if some are already defined in the Entity data module. If no entities are defined Entity type is set by writing a name, and an entity with this name will automatically be defined in the Entity data module. In Model 1 an entity of type Train 1 is created. The frequency of the created entities is specified in 'Time Between Arrivals' in the dialog box. A distribution can be selected from the list in 'Type', e.g. Constant arrivals. The 'Value' defines the interval between arrivals.

'Units' sets the time unit to minutes, hours etc. In Model 1 the trains are set to arrive every second minute. 'Entities per Arrival' specifies how many entities are to be created at every time interval. 'Max Arrivals' set the maximum number of created entities from this Create module. 'First Creation' gives the time for the first created entity from this module. In Model 1 there is one train per arrival with a maximum of 4 arrivals and the first train is created at time 0.0 minutes. The number under the Create module (the red circle in Figure 19) indicates how many entities have been created and is updated during the simulation. When clicking on a flowchart module like the Create module, the data in the dialog box is also seen in the spreadsheet view, see Figure 20. Data can be modified either in the dialog box or the spreadsheet view. This examination focuses on the dialog boxes.

Create - Basic Process

	Name	Entity Type	Type	Value	Units	Entities per Arrival	Max Arrivals	First Creation
1	Create 1	Train 1	Constant	2	Minutes	1	4	0.0
2	Create 2	Train 2	Constant	2	Minutes	1	4	0.0

Figure 20: Create in spreadsheet view

The Station module and the associated dialog box are shown in Figure 21. Again the 'Name' is arbitrarily chosen and represents the name shown on the module in the model. In Model 1 the name is Station Hillerød. 'Station Name' is the name used internally in Arena and it is defaulted to 'Name' unless specified otherwise. 'Parent Activity Area' and 'Station Type' are set to default. 'Report Statistics' is chosen to include information about this station in the report which Arena generates with all the statistic details from the simulation.

Figure 21: Station module

The Process module shown in Figure 22 is where the train is delayed according to the time it is held back at the platform. 'Name' is the module name in the model, and 'Type' is set to Standard by default. In 'Action' Seize Delay Release is picked because the train is seized (it enters the platform), it is delayed (dwell time) and it is released (it leaves the platform). 'Priority' is set to Medium(2) by default. As explained a resource can be added to the Process module. The resource is added by clicking 'Add...'. 'Type' is set to Resource, and a 'Resource Name' is chosen arbitrarily. The quantity implies how many entities the resource can handle at a time. The platform resource in Model 1 can take one train at a time, and therefore the 'Quantity' is set to 1. In the bottom of the dialog box the delay is specified. The distribution of the 'Delay Type' can be picked from the list e.g. to Constant with a Value of 2 minutes. The train is constantly delayed 2 minutes according to the defined dwell time. 'Allocation' is set to Value Added by default.

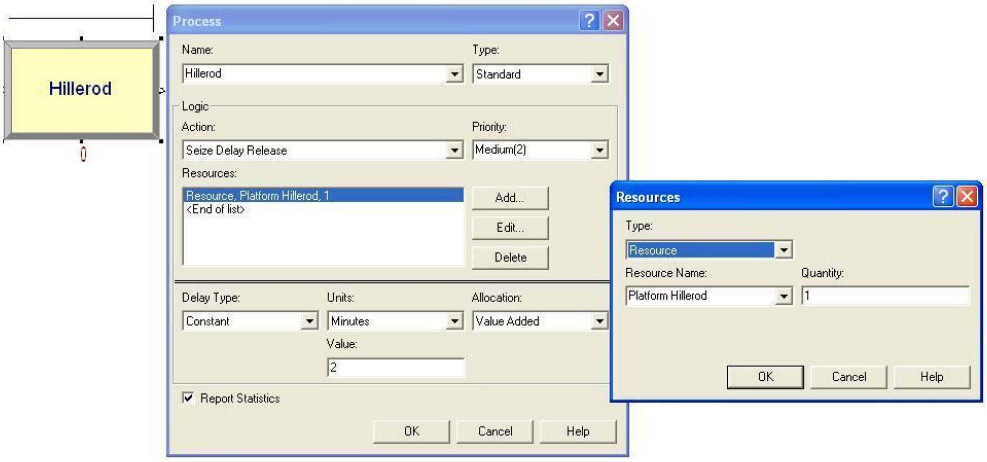


Figure 22: Process module

The Route module in Figure 23 is used to make the connection between stations time dependent. If normal connections (the lines) are used, the travel times between two modules are zero as mentioned. In the dialog box 'Name' is set to Route To Hundige. The 'Route Time' is the running time between stations and is set to 6 minutes. The train is routed to a Station module which is indicated in 'Destination Type' and the train in routed to Station Hundige in 'Station Name'.

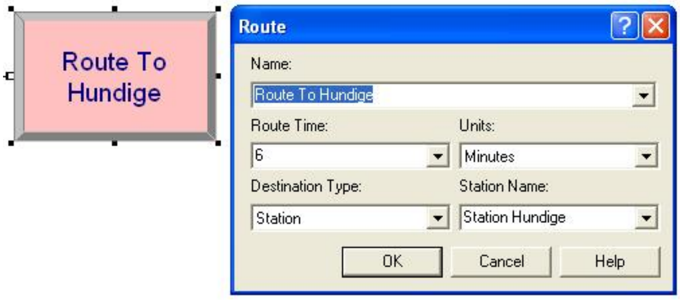


Figure 23: Route module

The four modules at the bottom of Figure 18 are similar to the ones just described and will not be examined. All the modules except the Route and Station modules are connected using the Connect button on the tool bar. Now the entities will travel from module to module during the simulation.

16.2.1 Verification of Model 1

To verify that Model 1 runs like it is supposed to Arena writes all the events and the times for the events in an output file, see appendix B. In the output file it is possible to check whether the right amount of entities (trains) are created, whether they all enter the stations, if the running time set in the route is 6 minutes as given and if the dwell time is 2 minutes as set in the Process module. Another way to verify the model is to follow the entities in the model either by making an animation or by following them move from module to module in the flowchart view.

16.3 Description of Model 2

In this chapter further descriptions of the simulation program Arena will be presented in the description of Model 2. Some details about the implementation of Model 2 are omitted because they are irrelevant for the description of the final model.

As opposed to Model 1 there are 3 stations in Model 2. The stations are arranged in separate submodels, see Figure 24. A submodel contains connected modules as the main model does. Entities enter and leave a submodel the same way they enter and leave the flowchart modules. Submodels are used to make a more structured and well-arranged model. The objective of Model 2 is to have two types of trains running between three stations. Trains ('normal') stopping on all station and a train ('fast') skipping one station. A additional objective is to experiment with added delay and the possibility of gaining time when delayed.

Figure 24: The three submodels in Model 2

In general all 3 stations are identical, except for a few individual features. Only the submodel for Hillerød station will be described in detail. Each station in the model (Hillerød, Allerød and Birkerød) is modeled as two separate stations representing the northern line platform and the southern line platform, each with a resource with a capacity of 1. Therefore the submodel for Hillerød includes a line of modules for the northern platform and a line of modules for the southern platform. Only the modules for the southern line are described since the modules for the northern line are similar. The submodel Hillerød is seen in Figure 25.

In Model 2 the following flowchart modules are used: Create, Station, Route, Process, Decide, Assign, Hold, Seize, Delay and Release. The first four modules have already been described in Model 1. The remaining modules will be described in the review of Model 2. Most modules are named by default, since no two modules can have the same name in Arena. This is done to simplify the process when new stations are created to expand the network; otherwise every time a module is copied it needs to be assigned a new individual name.

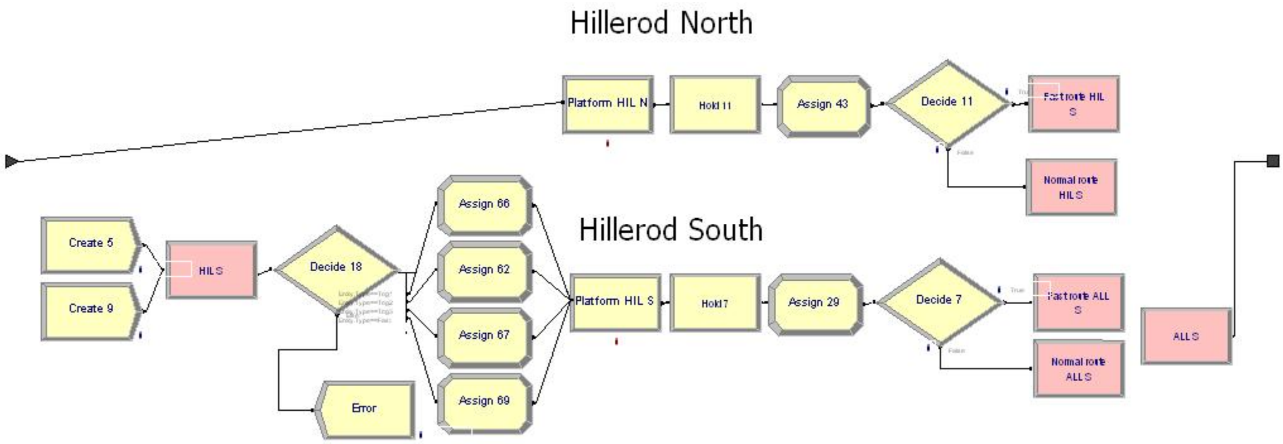


Figure 25: The submodel for Hillerød Station

The dwell time at the stations in the model is set to 2 minutes if no delays occur. The running times are calculated according to the departure times from the timetable from 2003 for DSB S-tog. All running times are represented in a matrix of variables called *Running_Times*. All departure times are represented in a matrix of variables named *timetable*.

Initially the trains are created as entities in the Create modules. There is one module that creates the trains for the 'normal' routes and one that creates trains for fast routes. The first creation is done 2 minutes before the first scheduled departure from the station, because the dwell time is set to 2 minutes. Only 1 normal line train is created in Hillerød and 1 in Birkerød since 2 trains are enough to fulfill all scheduled departures in this small model, due to the short cycle time in the network. Also 1 fast line train is created in Hillerød. Next the trains are send to the station HIL S, which represents the arrival into Hillerød southern station.

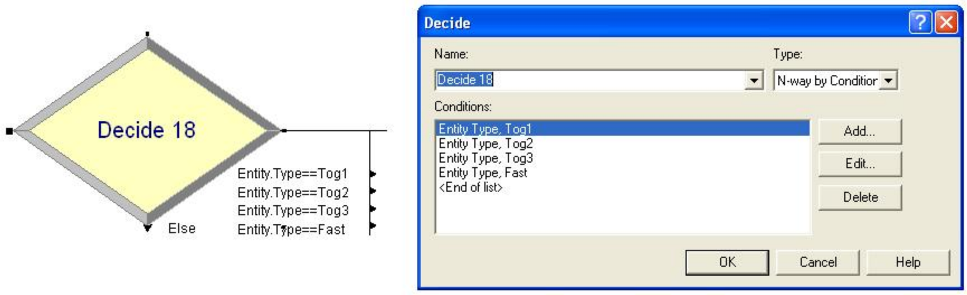


Figure 26: The N-way by condition Decide Module and dialog box

Since the timetable from DSB S-tog is made with 3 trains of the same type departing from each stations within an hour, there is a specific entity type for the first, second and third train on the 'normal' line in each hour called Tog1, Tog2 and Tog3. This differentiation is made to connect the three 'normal' trains to the right departure times in the timetable. Also there is an entity type representing fast trains, trains that stop only at Hillerød and Birkerød. *Entity.Type* is an Arena defined attribute. When a train arrives at Hillerød South the entity is changed to the next train that is scheduled to depart from the station. This is done in the 'N-way by condition' Decide Module, in Figure 26, and the subsequent Assign module that inspects which entity type the train represents now and whether it should be changed to another type to match the next departure in the timetable. Since an 'N-way by condition' Decide Module evaluates to either true or else a Dispose module is used as a dummy module to catch entities which do not fit any entity type (of course this should never be the case).

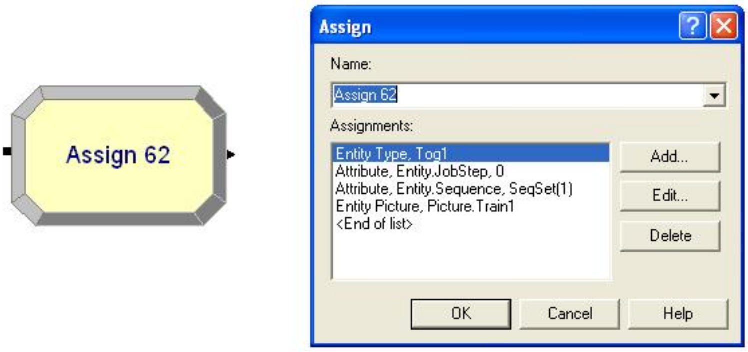


Figure 27: The Assign Module and dialog box

The Assign module in Figure 27 shows one of the four Assign modules that updates the entity types. The module is also used to update some other attributes which make sure that the train uses the right sequence of stations.

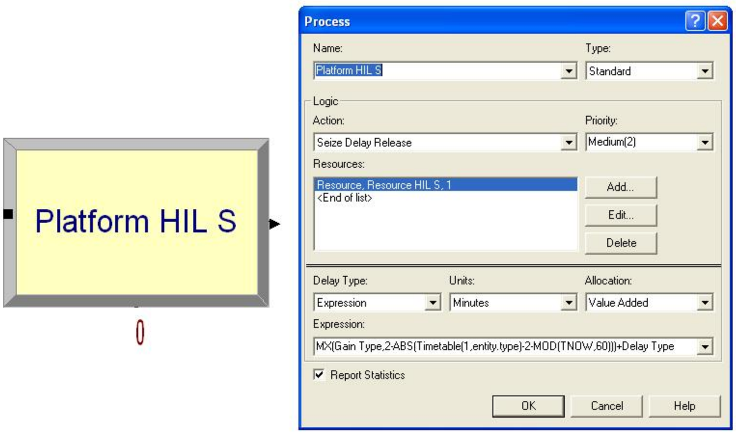


Figure 28: The Process Module and dialog box

The next module is a Process module and represents the platform at the station, See Figure 28. This is similar to the Process module in model 1. A process can be split into a Seize, Delay and Release Module, as is the case for station Allerød. This is because Allerød has the possibility of trains passing as the only one of the three stations. At Hillerød the three functions are kept in one Process module. The delay represents the dwell time at the platform. The process includes a resource which specifies the capacity of the platform. The resource also has a queue. The queue uses a ranking of first-in-first-out, since trains are not allowed to overtake. In Model 2 there is only one way for an entity to be delayed which is at the station. The reason for this is that it does not matter whether a train is delayed at the station or at the route between two consecutive stations.

There are two possibilities for gaining time once delayed: At the station (shorter dwell time) or at the route between stations (shorter running times). These might not be possibilities for all stations or routes in the network and the amount of time to be gained may vary. How much time can be gained is calculated according to a random gain time distribution between 1 and 2 minutes.

How much a train is delayed is calculated from a delay time distribution. Both gain distribution and delay distribution are represented as Expressions in the model, and are evaluated each time a delay or route is used. Expressions are defined in the Expression data module in the Advanced Process project bar.

When a train reaches a platform, it is checked whether the resource (platform) is already seized by another entity. If this is the case it joins the queue in front of the process. Otherwise it seizes the resource. Then it is checked whether the train is delayed for arrival, i.e. if the scheduled arrival time (departure time minus scheduled dwell time) is larger than the current simulation time TNOW. If the train is on time, it will not be possible to gain time, since this would imply a departure prior to the scheduled departure time. If the train is late the dwell time is determined according to the delay. The dwell time is calculated as a maximum of the amount of gain time and the scheduled dwell time minus the delay i.e. if a train arrives 1.5 minute late and it is possible to gain 1 minute the dwell time will be MAX(1, 2-1.5)=1 minutes. Further delay at this station (if any) is also added to the dwell time. The total dwell time is calculated using an expression as can be seen in the dialog box in Figure 28. The MOD function is used to make sure that even though the simulation time is larger than 60 minutes, the same timetable departure times can be used.

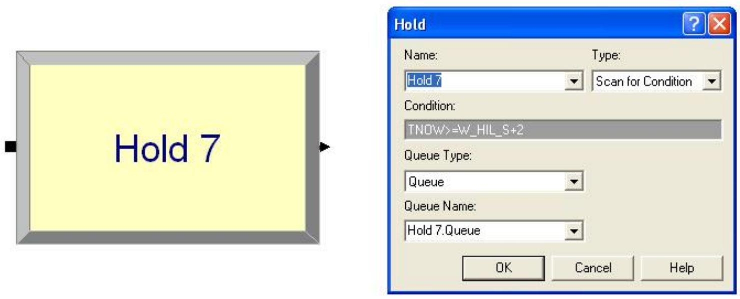
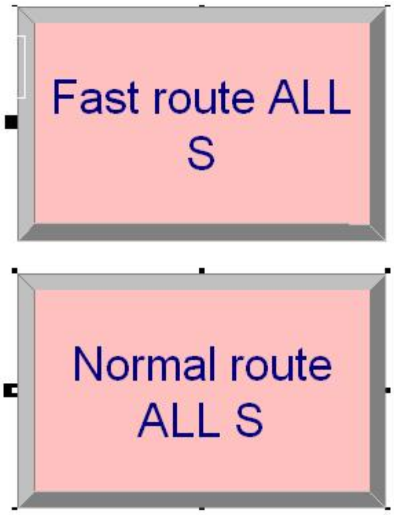


Figure 29: The Hold Module and dialog box

The minimum headways in Model 2 is 2 minutes, hence no two consecutive trains can traverse the same route within 2 minutes. This is taken care of in the model by the Hold module, see Figure 29. Each time a train has passed a Hold module a variable *W_HIL_S* is set to the current simulation time TNOW in the subsequent Assign module. Then the Hold module holds all arriving entities until TNOW is larger than or equal to *W_HIL_S+2* i.e. two minutes later the next entity can pass the Hold module. This is done by holding the entities according to a condition, see the dialog box in Figure 29. The entities which are held back are placed in a queue. The queue uses a ranking of first-in-first-out, since trains are not allowed to overtake.



Route - Advanced Transfer

	Name	Route Time	Units	Destination Type
1	Normal route ALL S	Running_Times(1,2)	Minutes	Sequential
2	Fast route ALL S	Running_Times(1,2)-MN(1,TNOW-timetable(1,entity.type))	Minutes	Sequential

Figure 30: The Route Modules and dialog boxes

There are two possible routes from a station to the next, see Figure 30 which displays the Route modules. A Decide module is used to check whether the train is delayed and if this is the case the train is send to the fast route, which means that it might be possible to gain some time on the route. Otherwise it is send to the normal route. If a train is late when it is to be routed to the next station, there is a possibility of gaining time at the route by shortening the running time i.e. speed up the train. This way the routing time can vary according to the delay of the train.

The last module is a Station module which represents the next station in the model, where the entity needs to be routed.

16.4 Animation

Animation of the simulation in Arena does not have a direct effect on the results of the simulation, but can illustrate the system that is modeled. The animation can also be used in the verification process to some extend. The animation in Model 2 is shortly described to give an idea of how an animation is created in Arena.

In Figure 31 a segment of the animation in Model 2 is seen. To make an animation of Model 2 the important elements are Station animations, Route animations and queues.

The characteristics of a Station animation and the Route animation are defined by clicking on the Station or Route button in the Animate Transfer toolbar. See Figure 32. Station and Route characteristics in the animation can be edited when the dialog first appears before placing the objects, or by

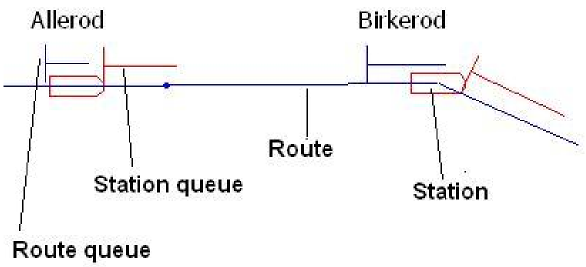


Figure 31: Animation elements

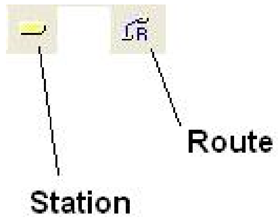


Figure 32: Animation icons

double-clicking on an existing object. Figure 33 shows a dialog box for a station, here the identifier is set to the Station module in the model, this specific station in the animation should represent (in this case Allerød North). The Station animations are inserted in the animation by using the station icon in Figure 32 and the station is connected to a specific station module in the model. Afterwards the Route animations are drawn between the stations by using the route icon in Figure 32.

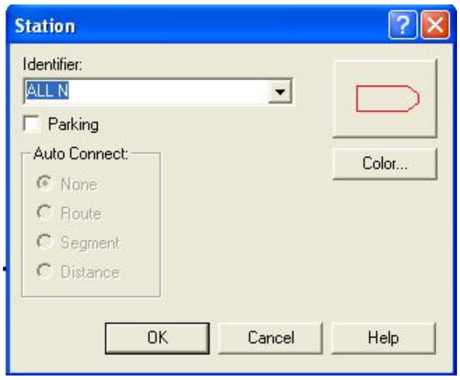


Figure 33: Station dialog box

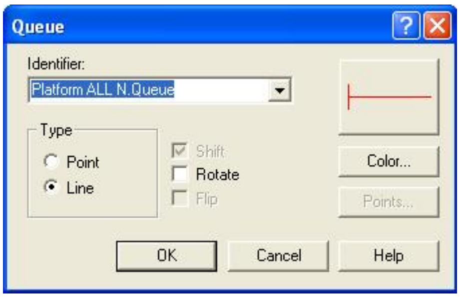


Figure 34: Queue dialog box

The queues in the animation are also connected to specific resources or hold modules in the model, where entities can be held back. Figure 34 shows a dialog box for a queue in the animation. Note that there are two queues for each station in Figure 31, a queue for the Resource module (Station queue) and a queue for the Hold module (Route queue). The queues are the same as the ones that appear above the flowchart modules when the flowchart modules are created.

16.4.1 Verification of Model 2

The verification of Model 2 is a little more complex than the verification of Model 1 because delay occurs. Again the output file is used to verify that the model runs as expected. The main test is to see whether the dwell and running time are calculated correctly according to the delay of each train.

If no delays occur (are added) the trains should be running according to the given timetable but if delays are added, then the dwell and running time should be reduced to re-establish the plan.

Different tests were run with the Gain Type set to 1. This means that the minimum dwell time at the stations is 1 minute as opposed to the scheduled dwell time of 2 minutes. The running time can be reduced with 1 minute as the maximum. The test results, taken from the output file, are shown in Table 3. If the Gain Type follows a distribution the simulation becomes stochastic. Then the results will be different and could not be predicted.

It is also verified that the Hold and Queue modules behave as intended. By reading the output file it is verified that the trains are held back to maintain the safe headway and that the trains are held in queues for the stations and released by the order first-in-first-out.

Delay	Result
0 minutes	The trains are running according to the plan.
1 minute	The delays are eliminated because one minute can be gained at the station OR at the route, according to minimum dwell and running time.
2 minutes	The delays are eliminated because one minute can be gained at the station AND at the route, according to minimum dwell and running time.
2,5 minutes	The delays accumulates because at most 2 minutes can be gained at the stations and routes.

Table 3: Verification of Model 2

17 Description of the final model

The prototype for the final models is build on data from the timetable from 2003. The final model is build as a generic model. The basic idea behind the generic model is that all the stations in the network can be represented by the same submodel in Arena, because all stations are somewhat similar. The individual characteristics for each station are stored in variables.

The idea in Model 2 was to make a submodel for each station in the network. This would give approximately 80 almost identical submodels for the S-train network. In the final model the differences, e.g. whether it is an end station or not are stored in variables and only one submodel is used to represent all the stations. This makes the model simpler because fewer modules are used. The same modules represent all 161 stations in the network - approximately 2 for each station in the real system depending on the number of platforms. A line specific sequence of stations specifies which stations the trains should visit, but all the entities (trains) in the model enter the same submodel every time they enter a station even though it is not the same station. A specific set of variables represent the particular station the train enters. The variables specify the dwell time for the specific station, whether the particular station is occupied by another train and for example whether the specific train should stop or pass this specific station. In Table 5 all the variables used in the model are explained. The table is an overview and the variables will be used later in the description of the final model. Attributes are also very important to differentiate the stations from each other when they are represented in the same submodel. As explained earlier attributes only pertain the entity it is connected to as opposed to variables which are global. Each entity (train) in the network have attributes defining their scheduled arrival and departure times, the line in the network they are covering, the current and next station, the specific step in the sequence of stations for the line, the direction in the network (going south or north) and other train specific data. See Table 4 where all the attributes for the trains are explained. This table is also an overview and the attributes will be used later.

Both attributes and variables represent numbers. The attributes are all named with *Att* in the beginning. This is done to differentiate between the use of attributes and variables. The attributes are used as indexes to the variables with more dimensions. All the attributes are modified during the run of the simulation and cannot be predefined. Variables on the other hand are always predefined. Some of the variables used in the final model are modified during the run of the simulation others are not.

Attribute	**Description**
AttLine	Represents the line the train should follow. There are 10 different lines in the timetable from 2003. 1 represents Line A, 2 Line A^+, 3 Line B, 4 Line B^+, 5 Line Bx, 6 Line C, 7 Line E, 8 Line Ex, 9 Line H, 10 Line H^+.
AttStation	The current station. There are 161 stations in the model. Every station in the network is represented by two or more stations in the model. A station for trains going north and a station for trains south. This represents the two tracks with trains going in opposite directions. If a station has e.g. two tracks in each direction, the station is represented with 4 different numbers. See appendix C where all the stations are represented and numbered. For example Holte station is represented with number 30 and 110 respectively the north and the south going track. København has two tracks in each direction and is represented with respectively number 44, 45 and 124, 125. When a train/entity going north enters e.g. Holte it enters station 30. When a train going south enters København it enters station 124 or 125 depending on the line. All lines are scheduled to use a specific platform if there are two tracks in the same direction.
AttNextStation	This attribute represents the next station where the train should be routed to.
AttTime	Represents the scheduled time for the train as the sum of running and dwell times prior to the current station. *AttTime* represents the scheduled timetable for each train. This attribute is used to verify whether the train is on time or late.
AttStep	The step in the sequence (a variable) given for each train line. The attribute *AttStep* is increased by one every time the train leaves a station. When the step reaches the length of the sequence it starts from 1 again.
AttNextStep	Is the next step in the sequence.
AttDirection	Defines whether the train is travelling south or north.

Table 4: Attributes

The idea behind Model 2 was to make a submodel for each of all the stations in the network. This

Array of variables	**Description**
Dwell(AttStation)	The variable *Dwell* is an array with 161 rows with dwell times for the 161 stations in the model. See appendix D
MinDwell(AttStation)	The variable *MinDwell* is also an array with 161 rows with minimum dwell times for the 161 stations.
Running(AttStep,AttLine)	Is an array defining running times between stations for all lines. The longest line defines the first dimension of the array and the number of lines defines the second dimension. See appendix E
Occup(AttStation)	This array with 161 variables is used to make sure that there is only 1 train at the station at a time. The variable is set to one for a particular station, when a train enters this station. It is set to zero when the train leaves the station. This way only one train can visit each station at the time even though all the stations are represented by the same submodel.
Headways(AttStation)	This array with 161 variables defines the headways after the particular station. Headways are the minimum time interval between two consecutive trains.
WaitHeadways(AttStation)	When a train leaves a station *WaitHeadways(AttStation)* is set to the current simulation time (TNOW). The next train leaving the same station is held until TNOW is greater than *WaitHeadways(AttStation)* + *Headways(AttStation)* to make sure the right headways are kept on the routes between stations even though all the routes are represented by the same submodel.
StationTypes(AttStation,AttLine)	Indicates whether the train on the given line should stop on the specific station. If *StationTypes(AttStation,AttLine)= 1* the train should stop, if *StationTypes(AttStation,AttLine)= 3* the train should not stop on this station and if *StationTypes(AttStation,AttLine)= 2* the station is an end station. Virum station is e.g. represented with a 1 for lines B/B$^+$ and a 3 for lines A and E. Holte station is represented with a 2 for lines B/B$^+$ because these two lines terminate in Holte and a 1 for lines A and E. See appendix F
Sequence(AttStep,AttLine)	The sequence of all the stations on each line, including the stations where the trains covering the line does not stop. For example the sequence for line A is (Hillerød, Allerød, Birkerød, Holte, Virum, ..., Ishøj, Hundige, ..., Hillerød). The sequence represents the stations in both directions. The sequence, as all other variables, are represented with numbers. See appendix G
SequenceLength(AttLine)	The lengths of the sequences for all lines.
MinShunt(AttStation,AttLine)	The minimum shunting time at the end stations defined as the minimum time required to turn around at the specific end station.
ChooseRec	This variable is set to 0, 1, 2 or 3 defining whether no recovery method is used (set to 0) or whether one of the 3 recovery methods are used (set to 1, 2 or 3). A Branch module in the station submodel leads to one of the four choices.
WarmUp	Because all trains are inserted at the end stations for each line, there is a warm up period before the system is actually running according to the situation in the real world. Regularity is not calculated during the warm up period and delay are not added until TNOW is greater than the warm up time. The warm up period is set to 250 minutes, because this is approximately how long time it takes before all the trains are running.
MaxNoNextQueue	This variable is used to hold back trains if the queue for the next station is to long.

Table 5: Variables and Arrays in Main Model

approach would have been time consuming but easy to implement, because the small differences at the stations could be implemented directly in the submodel representing the specific station, but very challenging to maintain because even few changes would have to be repeated for all station submodels. Furthermore it would have been a lot of work to copy-paste and connect all the station submodels. The final model needs a few more variables to separate the stations from each other when all stations are represented by the same modules, but this also means that changes only have to made once and the model becomes more well-arranged.

The final model can be split into separate parts:

- The main model, where entities (trains) are created.
- Station submodel, representing all the stations in the network.
- Two submodels where regularity and reliability are calculated.
- Three submodels with the three recovery methods.
- A submodel that reads running and dwell times from Excel and writes regularity data to text files.
- Animation.

These different parts of the model will all be described in the following sections.

17.1 Main model

The main model is where the different entities (trains) are created and entering the system. The main model is shown in Figure 35. 10 different types of entities are created for the model of the timetable from 2003, one for each line in the network. The number of created entities of each type depends on the number of train units needed to cover the line with an interval of 20 minutes between each train. Table 6 shows the different entity types, the quantity created and the station they enter first. Each entity is created according to the first departure time in the timetable and then every 20 minutes the next entities are created.

Every Create module in the main model is followed by an Assign module, where the important attributes *AttLine*, *AttTime*, *AttStep* and *AttStation* for each train are assigned. The attribute *AttLine* depends on the line the created train should cover, *AttTime* is set to $TNOW$ (the current simulation time), the time the entity is created and *AttStep* is set to 1. All entities are created in the north end because the first station in the sequences are the north end station. The attribute *AttStation* is set to the first station, given by *Sequence*(*AttStep*, *AttLine*). The only assignment that are different for the 10 different Assign modules are *AttLine*, which depends on the type of the train.

The next Assign module 'Choose Recovery Method 0 or 1 to 3' assigns the variable *ChooseRec* to 0,1,2 or 3. If *ChooseRec* $= 0$ no recovery method is activated. Otherwise one of the three recovery methods are used later in the model.

Entity type	**Quantity**	**Starting station**
Train A	8	109 (Hillerød)
Train A^+	6	159 (Østerport)
Train B	7	110 (Holte)
Train B^+	6	110 (Holte)
Train Bx	5	106 (Hellerup)
Train C	6	123 (Klampenborg)
Train E	9	109 (Hillerød)
Train Ex	6	106 (Hellerup)
Train H	10	97 (Farum)
Train H^+	10	97 (Farum)

Table 6: Entities created for the timetable from 2003

Now the entity enters the submodel Station meaning that the train enters the station specified by *AttStation*. The Station submodel will be examined in the next section. When the train is routed from the station it leaves the submodel and returns to the main model where the attributes *AttStep* and *AttStation* are updated. Then the entity enters the submodel again, meaning that the train visits the next station represented by the updated *AttStation* and so on. In this way the trains drive from station to station following the sequence of stations defining the line in the network. As an example line B ($AttLine = 3$) starts in Holte S ($AttStation = 110$, $AttStep = 1$) then drives to Virum ($AttStation = 55$, $AttStep = 2$) and so on .

17.2 Station submodel

The Station submodel, seen in Figure 36, represents all stations in the network and is build similar to the three stations in Model 2. All the different modules in Figure 36 will be examined thoroughly in smaller segments in the following.

In Figure 37 the first four modules in the submodel are shown. These modules updates $AttNextStep$ and $AttNextStation$ in the following way. $AttNextStep = (AttStep{+}1)$ modulus $SequenceLength(AttLine)$. The attribute *AttStep* is increased by one, but must stay below the length of the sequence it is scheduled to follow. When $AttNextStep$ reaches the length of the sequence the train has traversed one whole round and starts over. $AttNextStation$ is set to $Sequence(AttNextStep, AttLine)$. Both the current and the next station and step are used in the rest of the submodel, therefore the additional attributes $AttNextStep$ and $AttNextStation$.

Next the entity enters a Decide module, followed by two Assign modules, see Figure 38. Here the direction is set to 0 if the train is going south and 1 if it is going north. All northern station are numbered from 1 to 80, and the southern are numbered from 81 to 161.

In Figure 39 the third part of the Station submodel is shown. The train enters the Hold module 'Hold

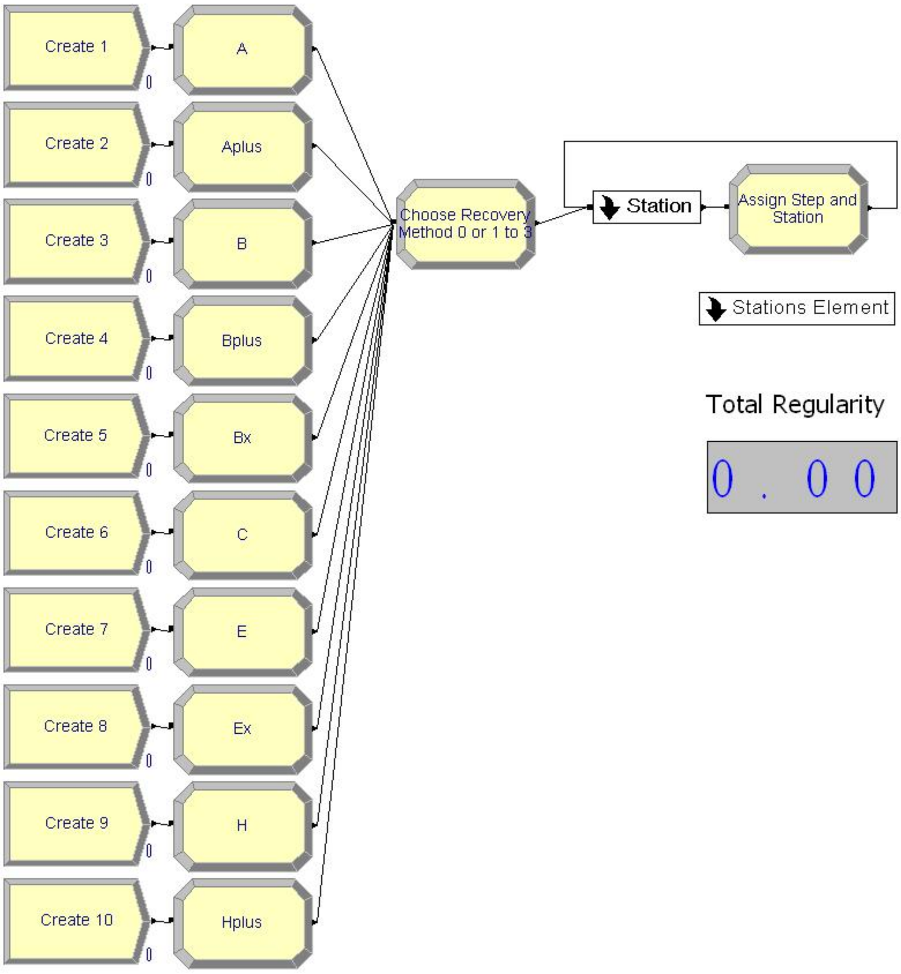


Figure 35: Main Model

if Station occupied'. The train is held back if another train is occupying the station. The entity is held until $Occup(AttStation) == 0$. When leaving the Hold module $Occup(AttStation)$ is assigned to 1 in the following Assign module. When the train occupy the station other trains will be held back. In the next module it is decided whether the train is scheduled to stop at the station or not. If $StationTypes(AttStation, AttLine) == 3$ the train is not scheduled to stop on this station. If $StationTypes(AttStation, AttLine) == 1$ or 2 the train dwells at the station (is delayed). All trains must occupy the station even though they do not actually stop at the station. This is similar to the real system, where the trains cannot drive past the station on a second track.

In the next four modules shown in Figure 40 the train is delayed if it dwells at the particular station. If the train arrives on time (if $AttTime = TNOW$) it is delayed $Dwell(AttStation)$. If the train on the other hand arrives later that scheduled (if $AttTime < TNOW$) it can gain time by only being delayed between Dwell and Min Dwell. The train can never leave earlier than scheduled. Next in the Assign module $AttTime$ is updated by $AttTime = AttTime + Dwell(AttStation)$. Note that $AttTime$ represents the scheduled time.

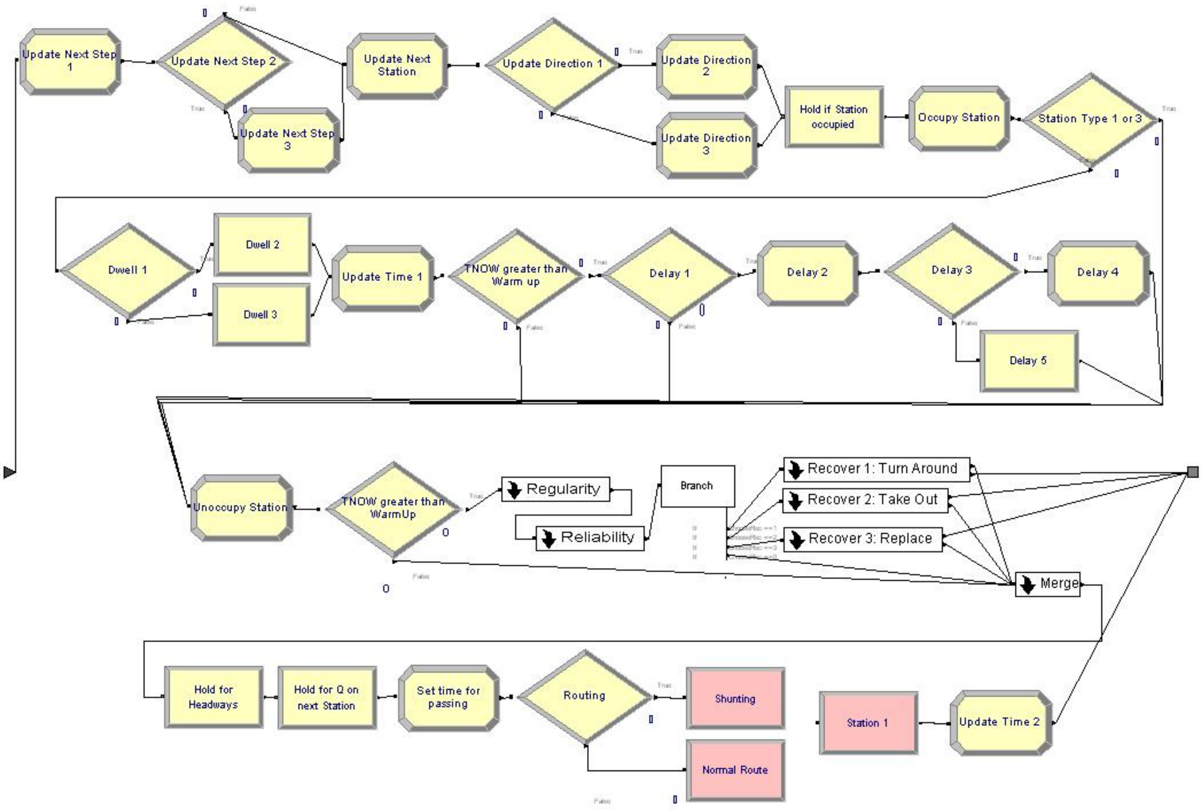


Figure 36: Station submodel

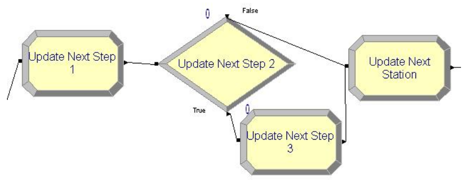


Figure 37: Updating the attribute AttNextStep

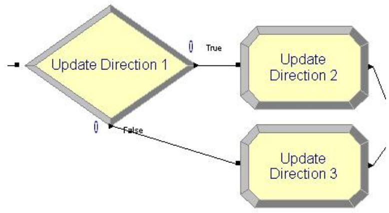


Figure 38: Updating the attribute AttDirection

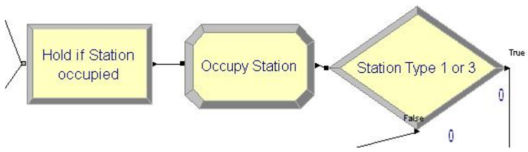


Figure 39: Hold if station is occupied

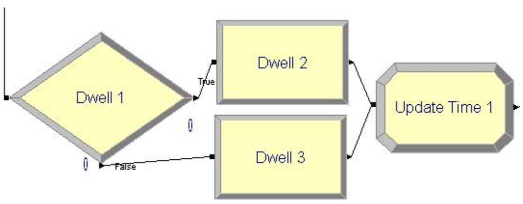


Figure 40: Dwells at station

In Figure 41 the next modules in the submodel are shown. Here the entity may be delayed. The first Decide module controls whether the warm up period is passed (if $TNOW > WarmUp$). Delay is only applied after the warm up period. In the next modules the train is delayed according to a distribution made from historical data.

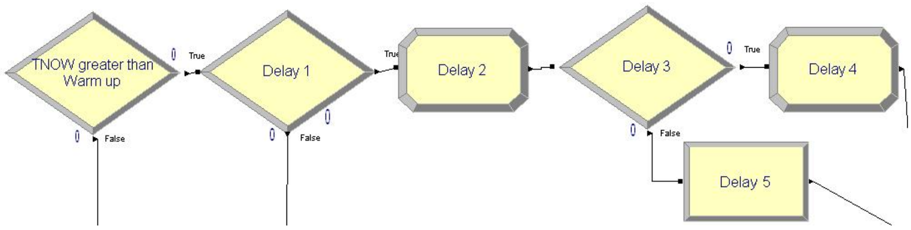


Figure 41: Delayed at station

In the Assign module shown i Figure 42 the train 'leaves' the station and $Occup(AttStation)$ is set to 0, to indicate that the station is idle.

Figure 42: Station is unoccupied

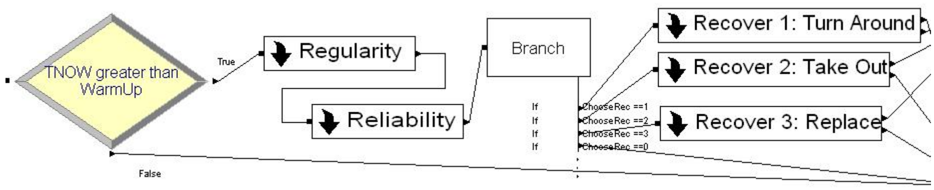


Figure 43: Submodels

Figure 43 shows submodels where the regularity and the reliability is calculated and where one of the four recovery methods are activated. These submodels are examined later. The Branch module is similar to the Decide module.

In the submodel Merge shown in Figure 44 the B and B^+ line trains are merged. In Figure 45 the details of the Merge submodel is seen. The first Decide module examines whether the train is a B or B^+ line train (*AttLine*), whether the station (*AttStation*) is Høje Taastrup where line B and B^+ are merged and whether line B^+ is still running (not taken out). If this is the case the attribute *AttLine* is updated. If line B^+ is cancelled the merging is not possible and the B line trains is delayed for 10 minutes, which could have been saved by merging with line B^+. Finally the attribute *AttTime* is updated because of the delay.

Figure 46 shows the last part of the modules in the Station submodel. This is where the train is routed to the next station.

Figure 44: Merge submodel

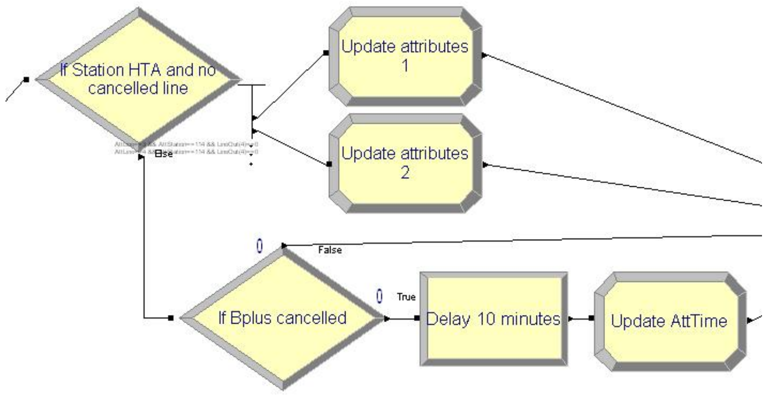


Figure 45: Merge submodel in details

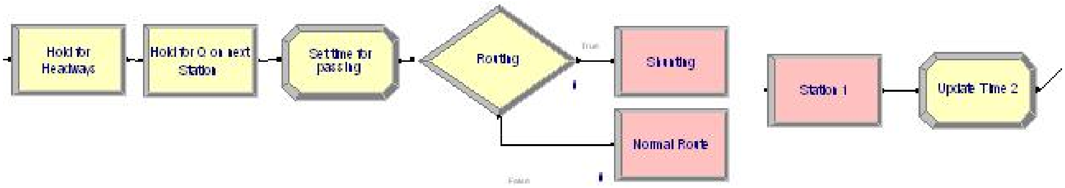


Figure 46: Routing

The first Hold module 'Hold for Headways' makes sure the headways are maintained. The second Hold module 'Hold for Q on next Station' holds the entity until the queue for entering the next station ($AttNextStation$) is smaller than a given threshold ($MaxNoNextQueue$). In Arena an unlimited number of trains can be held in a queue for each station, but this is not the case in the real system. The maximum number in queue depends on the length of the route between the stations. By holding the trains the model becomes more realistic.

The train is routed to the next station ($AttNextStation$) in the sequence .
If $StationTypes(AttStation, AttLine) == 2$ it is routed between two end station. On these routes it is possible to gain time, therefore there are two different Route modules. After being routed the train enters the Station module representing the next station. The last module in the submodel is an Assign module, where $AttTime$ is updated by $AttTime = AttTime + Running(AttStep, AttLine)$.

Now the train leaves the Station submodel and reenters the Main model. Here the attributes $AttStep$ and $AttStation$ are updated ($AttStep = AttNextStep$ and $AttStation = Sequence(AttStep, AttLine)$), and the train enters the Station submodel again 'visiting' the next station on the line.

17.3 Regularity

As described in chapter 14.1 regularity can be used to determine the condition of the system, in connection with recovery of the system when disturbances occur. The regularity is calculated in the

Regularity submodel. The regularity indicates the percentage of trains that have been running according to schedule i.e. without being disturbed. The regularity is also used to determine when to begin to cancel lines or when to re-insert cancelled lines once the system has been recovered. Note that a delay below 2.5 minutes is not considered a disturbance.

In the model regularity is calculated in the Regularity submodel every time a train passes through a station. Regularity is not calculated during the warm up period. Regularity is calculated both for the individual lines and grouped for all the lines. Regularity is calculated as

$$1 - \frac{\text{Number of departures}}{\text{Number of departures in total}}$$

The variables used in the regularity submodel are shown in Table 7.

Arrays	**Description**
Late(AttLine)	Array used to count the number of late trains on each line. Is used to calculate the regularity.
Reg(AttLine)	Regularity for each line.
TotalReg	Overall regularity.
TotalTrains(AttLine)	Number of trains on each line, through the regularity module. Is used to calculate the regularity.

Table 7: Variables and Arrays in Regularity calculations

Whenever a train arrives at the regularity submodel a counter of total number of trains passing through the regularity module is being increased. Then it is checked whether the train is late on arrival compared to the scheduled time ($AttTime$). A difference of more than 2.5 minutes is the threshold above which the train is considered late. If the train is on time i.e. less than 2.5 minutes late, the regularity is calculated for the whole system as well as for the individual line. If on the other hand the train is late on arrival, a counter of late trains on the specific line is increased. Then the regularity is calculated for the whole system as well as for the individual line.

The regularity submodel is build in Arena based on the following pseudo code:

```
Total Number of Trains(AttLine) = Total Number of Trains(AttLine) + 1

if TNOW  >= AttTime + 2.5
       Late(AttLine) =  Late(AttLine) + 1
end
Regularity(AttLine) = 1 - (Late(AttLine)/Total Number of Trains(AttLine))
TotalRegularity = 1 - (Sum of Late(all Lines)/Sum of Total Number of Trains(all Lines))
```

17.4 Reliability

As described in chapter 14.1 reliability can be used as a measure to determine the effect on the customer service as a consequence of the number of trains turned, trains replaced or lines cancelled. Naturally the fewer trains in the system, the higher possible regularity, so to measure the effect on customer service level, reliability is introduced. Reliability measures the number of actual departures from the stations compared to the scheduled number of departures.

The reliability is calculated in the Reliability submodel. The number of departures for each line is recorded in a variable $Rel(AttLine)$ in the situation with no delays. These numbers are used to calculated the reliability in the situation where delays occur, and where recovery is used. Reliability is calculated as $\frac{TotalTrains(AttLine)}{Rel(AttLine)}$. As an example say that 10 departures are scheduled for a line and 8 departures are actually happening due to cancellations, then the reliability is $\frac{8}{10} = 0.8$ or 80%. The reliability is calculated at the end of the simulation.

17.5 Recovery Methods

As described in chapter 15 DSB S-tog use several recovery strategies and methods. Because the main objective of this project is to study robustness in timetables and not to test recovery methods not all the methods are implemented. Three of the recovery methods are implemented in Arena to broaden the basis of comparison of the different timetables and to compare these three methods.

The recovery methods where trains are replaced at København station, where lines are taken out and where trains are turned around earlier than the end station are implemented in Arena and will be examined thoroughly in the following sections. These three methods are selected because they seem to cover different kinds of smaller and medium size disruptions and have different effects on the customer service level and therefore represents a broad selection of the different recovery methods used at DSB S-tog. These three recovery methods represent both re-establishing and re-scheduling strategies.

Attempts to implement a fourth recovery method, where trains can skip certain stations failed. The idea in this recovery method is to skip some stations on the line to gain lost time. As an example the B line could stop only in Lyngby between Hellerup and Holte (like the A line), instead of stopping at all the smaller stations as originally scheduled. Because of many problems in order to make this method work as planned it was excluded. Since the main objective of the project is not to test recovery methods this order of priority was made.

The recovery methods that are not implemented are partly omitted because they do not fit to the objective of the project. For example the recovery method about cancelling marshaling is omitted, since marshalling during the day is ignored in the model, because the experiments mostly concern rush hour where no marshalling is performed. Recovering from disturbances by dividing the network into a southern and a northern part is only done if very large disruptions like blockings on the track occur, and since a timetable can be robust concerning smaller disturbances only, this recovery method is also omitted.

17.5.1 Turn around before the end station

The idea in this recovery methods is that if a train is delayed more than it is possible to gain while shunting at the end station or more than a maximum time e.g. 5 minutes, it will turn around at a station prior to the end station.

At DSB S-tog this is a recovery method that is being used, and in principle it is possible to turn around at all stations. In practice trains are only allowed to turn around at larger stations, to give passengers a possibility of changing to other trains.

The stations in the model where it is possible to turn around are

- Ballerup - going south (except line C)
- Buddinge - going north
- Friheden - going south
- Glostrup - going south
- Hellerup - going north or south (except north for lines Bx and Ex)
- Holte - going north (except for lines B and B^+)
- Hundige - going south (except line A)
- København - going north or south
- Lyngby - going north
- Vanløse - going south.

It is not possible to turn around in both directions, because a train should not be allowed to visit only few stations and then turn around and run back. This assumption is made from a passenger service perspective.

When a train on a specific line has just turned around, the following train on the same line is not allowed to turn around. Otherwise it would be difficult for the customers to reach the outer stations in the network when disturbances and delays occur. Hence when a train has been turned, the next train is set to drive through to the end station, and then the next train again is allowed to turn etc.

In the model this is handled by setting a variable $LineOut(AttLine)$ for the line to 1 when a train has been turned, and then when the next train on the line (in the same direction) has reached the last station on the line where it is possible to turn around the variable is set to 0 again, making it possible for trains on the specific line to turn around. This should ensure that at least every second train runs all the way to the end station.

When a train has been turned around at a station it is being inserted at the scheduled time $AttTime$, where it should have left the station (going in the other direction). In the model the insertion is done by updating the scheduled time, delaying the train until it reaches the scheduled time and then releasing the train in the opposite direction.

In the following a pseudo code is given to show the implementation of the recovery method in Arena.

```
If (AttTime + buffer time at end station) < TNOW AND LineOut(AttLine)==0
    If AttStation == Turn around station
        set LineOut(AttLine) = 1
        set AttNextStep = SequenceLength(AttLine) - AttStep
        set AttTime = AttTime + Running(AttLine, AttStep)

        While AttStep < AttNextStep - 1 % update AttStep, AttStation and AttTime
                set AttStep = AttStep + 1
                set AttStation = Sequence(AttStep, AttLine)
                set AttTime = AttTime + Running(AttLine, AttStep) + Dwell(AttStation)
        end
        set AttStation = Sequence(AttNextStep,AttLine)
    end
end

Duplicate entity
Delay original entity for Scheduled time - Current time

Delay duplicate entity for LongRun(Line+Direction)
set LineOut(AttLine) = 0
Dispose duplicate entity
```

In Arena the if cases are represented by Decide modules and the assignments are handled in Assign modules. The trains are held back using a Delay modules. The Duplicate module creates an exact replica of the entity, which is used to set *LineOut* to 0 when the next passing train has passed the last turn around station on the same line in the same direction, which is determined by the variable *LongRun*.

The attribute *AttNextStep* determines the step in the sequence where the train will be inserted (in the opposite direction). The scheduled time *AttTime* is updated to reflect the scheduled time when the train must leave the station in the opposite direction.

17.5.2 Verification

All stations where it is possible to turn around for all lines are tested e.g. an A line train is delayed just before arriving at station København to make sure that the train is turned around and re-inserted again at the scheduled time (leaving København in the opposite direction). This is checked for line A at stations København S, Friheden S, København N, Hellerup N, Lyngby N and Holte N.

Similarly for all other lines, all stations where it is possible to turn, as well as re-insertion times, are checked one at a time.

Further more is it examined that when a train is turned the following train is not turned even though it is sufficiently late. This way at least every second train is running all the way from terminal station to terminal station.

17.5.3 Cancellation of lines

The idea in this recovery method is to cancel certain lines in the network, if there are disturbances in the system, which have caused trains to be delayed. When the system has recovered the trains which have been taken out should be re-inserted on their scheduled time. Cancelling lines should increase the buffer time among the remaining trains. This way delays should be eliminated.

At DSB S-tog there is a recovery plan that determines which trains should be cancelled e.g. if line A is sufficiently late line A^+ will be cancelled. The plan used in the model is given in Table 8 and resembles the one used at DSB S-tog. A similar relationship is used to re-insert the trains. The recovery method is used when medium size delays occur, which cannot be eliminated by using buffer times, will take too long time to recover or will cause delays to propagate into the entire system.

Delay on line	A	A^+	B	B^+	Bx	C	E	Ex	H	H^+
Cancellation of line	A^+	A^+	B^+	B^+	Bx	H^+	Ex	Ex	H^+	H^+

Table 8: Cancellation of lines

In order to decide when to cancel lines, when there are disturbances in the system, it is necessary to count how many trains have passed in the period when the regularity has been below some threshold called $TakeOutLimit$ e.g. 80%. This is done for the individual lines and in total for all lines using the variables *CountIrreg* and *CountTotalIrreg*. It has the purpose of making sure that the system is actually disturbed for some time before lines are cancelled, and not just disturbed for a short period which might be able to recover itself just by using buffer times at the end stations.

In order to decide when to put back lines that have been cancelled, it is also necessary to count how many trains have passed in the period when the regularity has been above 95%. This is done for the line and in total for all lines using the variables *CountReg* and *CountTotalReg*. It has the purpose of making sure that the regularity has been above 0.95 for some time before the trains are put back into the system. Otherwise the regularity might fall below 95% immediately when trains are inserted due to disturbances caused by these, or disturbances in the system that have not been eliminated yet.

As described the regularity is calculated each time a train passes through a station, see chapter 17.3. The thresholds for cancelling and re-inserting trains are also calculated in the Regularity submodel.

In the following it is describes how this recovery method is handled in the model. When a train enters the Take Out submodel it is checked whether the overall regularity is below 0.95 and whether regularity on the line indicates that lines need to be cancelled. If both cases are fulfilled a variable *LineOut*(*AttLine*) is set to 1, to indicate that the corresponding line is taken out when the trains on the line reach a depot station. At the depot the trains are held back until the regularity has stabilized above 0.95 again.

It is assumed in the model that trains can be taken out at depot stations only, which is also the case in the real system. Depot stations are København, Hillerød, Farum, Frederikssund, Høje Taastrup, Køge, Ballerup, Klampenborg and Hundige.

When trains are taken out at the depots there is not always enough personnel at the depots to be able to put them back into the system, because the only personnel depot is at København. In the model it is assumed that personnel will be available at all times to make it possible to re-insert trains.

In the following a pseudo code is given to show the case for an A line train which is late and the corresponding A$^+$ line which will be cancelled. The method is similar for all other lines. The method consists of 3 parts: Adjust variables, Cancel line and Re-insert line.

```
if TotalRegularity <= 0.95
     if CountIrreg(Line A) >= CountLimit
         set LineOut(Line A+)=1     % Adjust variables
     end
end
if AttStation == Depot AttStation AND LineOut(A+)==1 AND  AttLine = 2 % (Line A+)
     Hold train until LineOut(Line A+)==0 % Cancel line

     When  LineOut(Line A+)==0   %Re-insert line
          Delay train until AttTime - AMOD(TNOW,TotalTourTime(Line A+))- Dwell(AttStation)
          set AttTime = TNOW
          set AttStep = AttStep - 1
          set AttNextStep = AttNextStep - 1
          set AttStation = Sequence(AttStep, AttLine)
          set AttNextStation = Sequence(AttNextStep, AttLine)
     end
end
if CountTotalReg  >= PutBackLimit
      set LineOut(Line A+)=0
end
```

AMOD is the real number remainder function in Arena. The amount of delay before re-insertion depend on the cycle time stored in the variable $TotalTourTime$. It is calculated in the following way to make sure that the trains are re-inserted at the time when they would have left the station on schedule.

As an example a train has a scheduled time for leaving København which is $AttTime = 107.5$. The line has been cancelled earlier and now the system has recovered to a regularity above 0.95, therefore the line should be re-inserted. The $TotalTourTime$ for this line is 120 min. and the current time is 300. So the train should leave København at $107.5 + 2 \times 120 = 347.5$ The current time 300 is given by

$300 = 2 \times 120 + 60$. It should be calculated how many rounds should be added in order for the train to be inserted at the right time, in the example 2 rounds should be added because $\frac{300-60}{120} = 2$. So the train should leave at

$$AttTime + \frac{TNOW - (TNOW \text{ modulo } TotalTourTime)}{TotalTourTime} \times TotalTourTime$$

which is $107.7 + 2 \times 120$, hence it should be delayed until the above minus the current time i.e.

$$\begin{aligned} & AttTime + \tfrac{TNOW-(TNOW \text{ modulo } TotalTourTime)}{TotalTourTime} \times TotalTourTime - TNOW \\ = \quad & AttTime - (TNOW \text{ modulo } TotalTourTime) \end{aligned}$$

which is $107.5 - \text{MOD}(300, 120) = 47.5$ so the train is delayed for 47.5 minutes until 347.5 and then it leaves København at the scheduled time. By using modulus calculations this inequality used to decide when trains should be re-inserted becomes very simple.

17.5.4 Verification

The recovery methods has been tested by considering two test cases

Case 1: Testing all lines in pairs e.g. A/A$^+$ and B/B$^+$, testing that the right line is cancelled.

Case 2: Testing that when a line is cancelled the trains will be inserted at the scheduled times.

Trains are delayed 6 minutes initially when created e.g. Line A is delayed 6 minutes initially and then A$^+$ should be taken out when the regularity falls below 0.8. When the regularity has risen above 0.95 and the count limit *CountTotalReg* has reached a threshold the trains should be re-inserted at the right time, and at the right station, dwell at the station and then continuing according to the sequence.

Test Case 1:

- First a single line A and a single line A$^+$ is tested.
- Then a single line A train and two line A$^+$ trains are tested.
- Last all 8 line A trains and all 6 line A$^+$ trains are tested.

Similarly test cases are made for all other lines.

Finally some cases are tested with delays on specific lines, when all trains are running in the system, and it is checked if the right lines are cancelled and re-inserted at the right times.

When all these test resulted in the right lines being cancelled and then re-inserted at the right times the method is concluded to function as intended.

17.5.5 Replace

The idea in this recovery method is that if a train is late a replacement train is inserted at København at the scheduled time according to the timetable. The late train will then be taken out for the day (disposed) when it reaches København (later than scheduled). This decreases the amount of time the network is affected by the disrupted train. Because the late train is taken out and replaced in København it only cause secondary delay on the way to København but not from København to the end station.

For example if an E line train is observed to be late when it reaches Hundige a new E line train is scheduled to depart from København going north at the time when the original E line train should have departed from København according to schedule. For a short while an extra E line train is now travelling the network. When the original E line train reaches København it is taken out and the right amount of E line trains in network is reestablished. If an E line train is late at Holte a new one is scheduled to departure from København going south. The original train is taken out when it reaches København.

The recovery method is activated when a train is later that a given threshold, which will be varied in the different experiments.

To make the recovery method realistic only two trains covering each line can be scheduled to be replaced at the same time (one train going south and one train going north on each line). This assumption is made out of concern for the passengers, to make sure not all passengers are affected by trains being replaced. Every second train on each line is travelling all the way through København to the end station without being replaced. When one train has been replaced and taken out in København, this train can be used to replace other trains. The driver of the replaced train also becomes available. Therefore it is reasonable to assume that there are enough trains and personnel to realize the recovery.

The variable $ReplaceData(i)$ holds the information about the trains scheduled to be replaced. In the timetable for 2003 with 10 lines this variable is an array of length 20. The rows represents the 10 different lines going north and south. Line A going south and north is represented in row $i = 1$ and $i = 2$. Line A^+ is represented by row $i = 3$ and $i = 4$ and so on. The row index is given by line and direction. The indexes are seen in Table 9.

Line	A		A^+		B		B^+		Bx		C		E		Ex		H		H^+	
Direc.	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N
Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Table 9: Index in the variable *ReplaceData*

The values saved in the variable indicates whether a train on the specific line and the specific direction is scheduled to be replaced. If a train is scheduled to be replaced $ReplaceData(i)$ is set to 1. No other train on the same line and direction can be replaced while $ReplaceData(i) \neq 0$. If an A line train going south is scheduled to be replaced $ReplaceData(1)$ is set to 1 and no other A line trains going south can be replaced. The new train is inserted at København, if the scheduled departure time has not been exceeded. If the new train is inserted *ReplaceData*(i) is set to 2, to indicating that the original train should be taken out, when it reaches København. This is done to make sure the original train is only taken out if it has been successfully replaced. If a train is scheduled to be replaced at a point of time later than the time it should depart from København according to the timetable, a new train cannot be inserted and the original train should not be taken out as planned.

When the original train reaches København and it is not taken out, *ReplaceData*(i) is set to zero, to indicating that another train on this line and direction can be replaced if necessary. If the train is taken out at København *ReplaceData* is set to zero, 25 minutes later. The reason for this is that only every second train covering each line in each direction is allowed to be replaced. The interval between two trains covering the same line is 20 minutes. The 5 minutes represents a buffer, if the next train should be delayed.

The following pseudo code shows how this recovery method is build in Arena. The method is separated in two parts. One covering København station where trains are taken out and all other stations where late trains are observed and scheduled to be inserted at København.

The first pseudo code is for all stations but København, where a train is scheduled to be replaced if it is later than a given threshold and no other train on the specific line and direction is scheduled to be replaced. The attributes *AttStation*, *AttTime* and *AttStep* for the replaced train at København is calculated in a while loop. The attribute *AttDispose* is set to 1 to indicate that the train should be taken out when it reaches København. Finally a new train is created by duplicating the original one. The attributes are set for the new entity and then it is delayed until it is scheduled to arrive at København. When the new train is released it enters København station.

```
if AttStation <> København AND train is late
        set row index i for ReplaceData variable % as in the table
        if ReplaceData(i) == 0
                set AttInsertTime = AttTime
                set AttInsertStep = AttStep
                while AttInsertStation <> København
                        AttInsertStep = AttInsertStep + 1
                        AttStation = Sequence(AttInsertStep,AttLine)
                        AttInsertTime = AttInsertTime + Dwell(AttStation)+
                        Running(AttInsertStep,AttLine)
                end
                set ReplaceData(i) = 1
                set AttDispose = 1
                set AttStation = Sequence(AttStep,AttLine)
                If AttInsertTime > TNOW % The train can be replaced
                        Duplicate entity
                        set AttTime = AttInsertTime
                        set AttStep = AttInsertStep
                        set ReplaceData(i) = 2
                        % The original train will be taken out when it reaches København
```

```
                        Delay until AttTime - TNOW
                end
        end
end
```

In the pseudo code for the model in København the train entering the station (København) is taken out if it has been successfully replaced.

```
if AttDispose == 1
        if ReplaceData(i) == 2 % the train has been succesfully replaced
                Delay 25 minutes
                set ReplaceData(i) = 0 % new trains can be replaced
                Dispose train/entity
        end if
else
        set ReplaceData(i) = 0 % new trains can be replaced
        AttDispose = 0
end if
```

17.5.6 Verification

To test the recovery method Replace it is important that the replacement train is inserted at the right time, that the original train is taken out only if it is replaced and that only one train on each line is replaced at the same time. The test is split in several cases.

One at a time a train on each line is created and delayed. This train should be replaced at København. The following values are examined:

- Testing whether the right index i is set for the variable *ReplaceData*, depending on line and direction
- Whether $ReplaceData(i)$ is set to one if the train can be replaced and later set to 2 if it is actually replaced
- See if the new train is inserted at the right time, step and station
- Control that the original train is disposed, but only if it has been replaced
- Make sure that a second train on the same line cannot be replaced before another train has travelled all the way to København with no interruptions. The following train should not be replaced but the third train should be allowed to be replaced if necessary
- Ensure that trains later on can get replaced, i.e. $ReplaceData(i)$ is set back to zero 25 minutes after the train is disposed.

This test is expanded by inserting the particular train at different station (at different steps in the sequence) and by inserting more trains at the same time and focusing on one of them. Finally all the trains are created as it is tested whether the same amount of trains are disposed as new ones are created.

17.6 Read/Write

The Read/Write module in the Advanced Process project bar is used to read running times and dwell times into the model, before the actual simulation begins. This is convenient since all calculations of times are handled in Microsoft Excel.

The Read/Write module is also used to write the regularities for each line and the overall regularity to a text file for each minute during the simulation. It is also used to write the reliability to an Excel file when the simulation is over. These files are used to study the results of the simulations.

17.7 Animation

In Figure 47 the animation of the entire S-train network is shown. The Route animations and the Station animations are shown and the colored lines represent the different lines. Each station is also represented by a name.

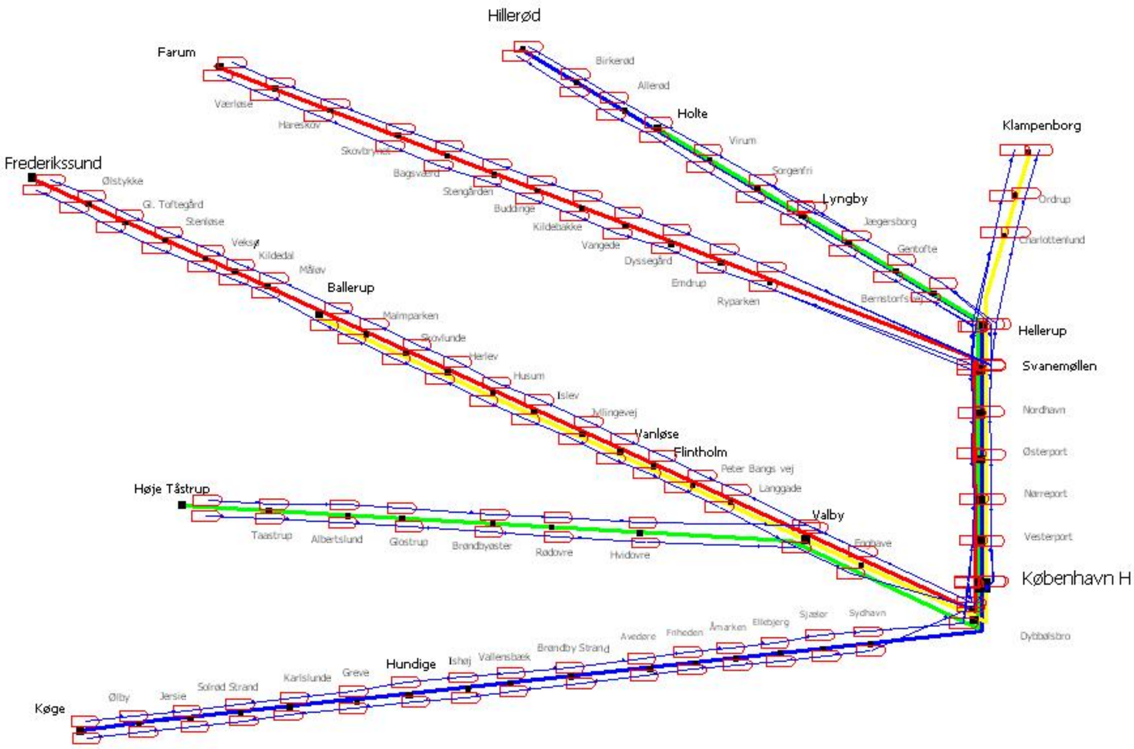


Figure 47: Animation of the S-train network

Because the final model is generic only one Station module is used to represent all the 161 different stations. This means that each Station in the animation cannot represent a specific Station module in the model. To specify in the animation which station to route to, a Stations element is used, where all the 161 stations are represented as a set. The Stations element specifies the total number of stations, their names and their associated intersections. Note that there is a difference between a Station module and a Stations element. The same set of 161 station is used in the Station module. To specify which station to route to next, the attribute $AttNextStation$ is used as index to this set of stations.

The different Hold modules in the model are also the same for all the stations, therefore a set of queues with 161 elements are made for each Hold module in the model. These queues are used in the animation.

In Figure 48 a screen plot of the animation in a running simulation is seen. Only the colored lines, the station names and the trains (entities) are visible in this animation. The trains (entities) are designed especially for this model.

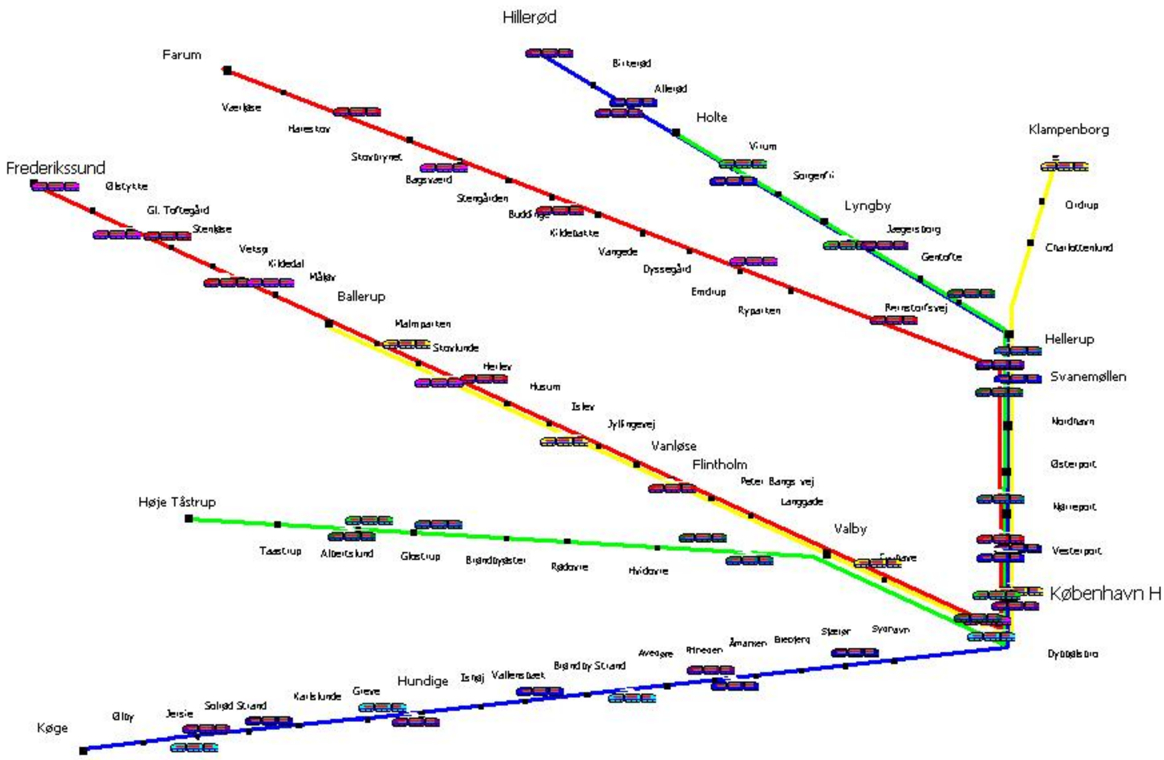


Figure 48: Screen plot of animation

17.8 Delays in the model

The distributions for delays in the model are generated from historical data from DSB S-tog of delays at the stations in the network. These delays are used as general patterns for delays. See chapter 9 for

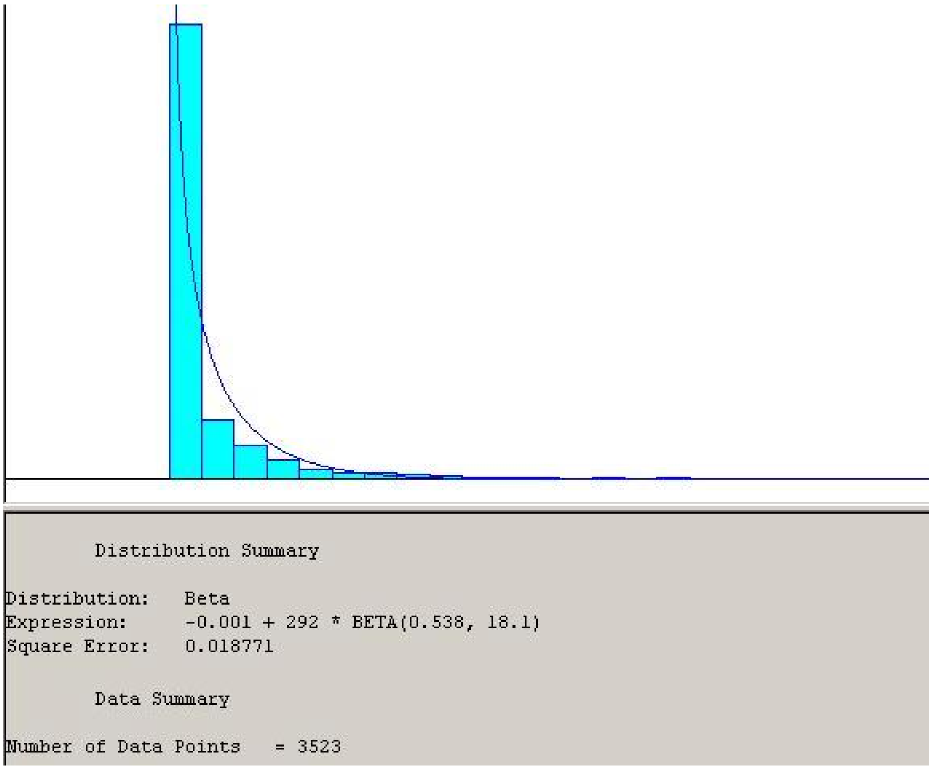


Figure 49: The output from the Input Analyzer

a description of causes of primary delays.

The delays in the historical data are taken from 4 Tuesdays in 2003, distributed over a year to allow for seasonal changes, and also distributed over the month to allow for daily changes. At DSB S-tog delays are allowed to be negative (i.e. an early arrival instead of a late arrival). This is not the case in the model where only actual delays are allowed. Therefore all negative delays are removed. Furthermore all delays above 2.5 minutes are recorded, hence secondary delays have to be removed before the distributions can be generated. The number of trains affected by each delay is recorded in the Data Warehouse at DSB S-tog and these reports can be used to remove all secondary delays manually, since the first (primary) delay is marked with a code.

The delay data for each station is approximated with a statistical distribution, which is used in the model. The statistical distributions are found using the Input Analyzer in Arena. The Input Analyzer is a tool for ´fitting´ statistical distributions to empirical data. The Input Analyzer finds the distribution best suited for representing the data. It is not necessarily the same type of distribution that fits the delay data best for all station. It is also possible to fit other distributions instead of the 'best fit' to the data, and in this case the Input Analyzer will return the parameters for the chosen distribution and also the square error when choosing this distribution. The output from the Input Analyzer when fitting a beta distribution to the delay data for København can be seen in Figure 49.

The beta distribution has been chosen for all the stations in the model, because this was the distribution that was returned from the Input Analyzer for the largest number of station. The beta distribution is also intuitively a fitting choice since the distribution should display a large number of small delays, and less occurrences of large delay values. This can be achieved with the beta distribution. It could also have been accomplished by using other distributions. Further more the beta distribution is recommended to represent delays in the article *Test schedule performance and reliability for trains stations* [4].

The reason for choosing the beta distribution for all station even though it is not the 'best fit' in all cases, is also to get a more homogeneous base for the experiments and as long as the same patterns of delays are used to evaluate all different timetables, the simulations should give an indication of the differences between these. In addition the square errors for the beta distributions are rather small compared to the best fit distributions.

There is a unique distribution for delays at each station, because of the variability in the historical data. The delays represent primary delays. In appendix H the delay distributions can be seen.

The probability of delays occurring has been fixed at 50% since it turned out that approximately half of the delays registered in the Data Warehouse at DSB S-tog were negative (i.e. the trains were arriving early). This is of course a worst case scenario since some negative delays would have cancelled out some of the the smaller (positive) delays over time.

18 Verification and validation of the final model

It is very important to make sure that the final model runs as intended. Test of the model is separated in two parts; validation and verification. Validation is the process of ensuring that the model behaves in the same way as the real system. If the model does not match the real system in all cases it is important to make some clear assumptions of why the model can be used to simulate the real system. Verification is the process of ensuring that the final model behave in the way it is intended according to the modeling assumptions made. This process is also known as debugging.

18.1 Validation and assumptions

One way of validating the model, is to compare it with the real system if such one exists. This was not possible in this project due to lack of suitable real world results.

Another validation is to study the assumptions made in the modelling phase. The model should be a representation of the real system except some assumptions that do not affect the credibility of the model and the results. The degree of assumptions depends on the objective of the simulation project. The model should be as accurate as possible and match the aim of the given project. Basically the more accurate the better, but too many detail might in some cases be redundant. The model in this project is not made to give an exact picture of the real system, but is used to compare timetables and to see how they differ according to real world scenarios. The most important thing in this project is that the comparisons are made on the same basis. Because assumptions are made and the model is not an exact representation of the real network the degree of detail is macroscopic. The following assumptions are made:

- The model only simulates worst case scenarios (rush hour). This assumption should not affect the results since the stability and the robustness of a timetable is assumed lowest in rush hour.
- The trains can never depart earlier than scheduled in the model. This is also considered a worst case scenario, and does not affect the results.
- Ringbanen is omitted from the model. This change does not have much affect on the results of the simulation, because Ringbanen is almost a separated network since it only interact with the other lines in the S-train network at very few stations. In the real system Ringbanen have a very high regularity and therefore it is excluded in this project.
- In the model all minimum safe headways are set to 1.5 minutes. Actual minimum headways in the real network are 1.5 minutes in the central area. Other places in the network the actual minimum safe headways are higher, but exact information could not be obtained and therefore headways are set to 1.5 minutes in the entire network in the model. This should not have an impact on the results, since all the timetables are compared on the same basis.
- Possible delays are only added at the stations. The delay follows a distribution made from historical data. Delays in the real system are added anywhere at the stations or on the routes, but the historical data is only gathered for each station. The data for a station therefore also contains the delay on the previous route, which makes this assumption very reasonable.
- The delay added in the model is made from historical data, which makes it very trustworthy. In the historical data both late and early trains are observed. Since an assumption about trains never leaving earlier than scheduled are made, the delay distributions are not completely correctly used in the model. In the model a compensation is made by only adding delay every second time a train enters a station (delay is added with 50% probability).
- To recover from disruptions (delays) by gaining time is only possible at stations or when turning around at end stations. This is done by using minimum dwell times and minimum shunting times. This assumption is very similar to the actual situation, since no data on gaining at routes are available and trains very rarely gain time while routing between stations, because the scheduled speed is close to maximum speed.
- In the real system there is only one track between Farum and Værløse, because the track is crossing an old bridge (Fiskebækbro). This mean that trains in the real system use the same track in both directions between these two stations. This is not modelled in the simulation model to simplify the modelling process and because it is mostly in the central area that trains affect each other.
- Some places in the model the tracks split from one to two tracks or merge from two to one track. The exact locations of the splits or the merging in the real system are different along the network. Splitting and merging tracks are implemented in the model in the following way. If the tracks split or merge between station A and Station B, the tracks split or merge right before the

station B. This is done to simplify the model. In the real network, if the tracks are merged right before station B or split right after station B it is considered the best case scenario because the tracks are kept double as long as possible. Opposite, if the tracks are merged right after or split right before station B it is considered the worst case scenario, because this case minimizes the length of double track. Since both best and worst case scenarios are represented, this assumption seems reasonable.

- Only the stations existing in the timetable from 2003 is used in all the timetables i.e. the station Danshøj is omitted. This should have no affect on the simulation, since the running times are modified to match this case. It is done to be able to compare the results for the different timetables on the same basis.
- The dwell times used in the timetable from 2003 is used in all the timetables. This does not affect the simulation, because the running times are calculated from the departure times in the timetable and the dwell time ($running = departure - dwell$).
- If data for minimum shunting times were not available they are taken as an average of all the minimum shunt times. Similarly missing dwell and minimum dwell times are added by considering the size of the station. This is only the case at very few stations and should not affect the results.

18.2 Verification

The verification is completed in several phases during the modelling. Every time new modules or submodels are added it is ensured that the model is running as intended. A lot of the verification is already done in the previous models build before the final model. In these earlier models it is verified that all the used flowchart and data modules are used correctly and behave as expected according to this particular simulation problem. It is further tested whether all the Decide modules split the entities in the expected directions, that the Hold modules hold the entities until the given condition is satisfied and that the right assignments are made in the Assign modules. The different expressions used for actual dwell times, delay and running time are also tested thoroughly in previous models and in the final model. In Arena it is possible to trace all attribute and variable values and information about the entities during the simulation, and also to perform the simulation step by step. This has been used in the verification.

The following is a description of the overall test scenarios.

1. First a very simple verification method is to allow only one single entity to enter the system and follow that entity step by step to ensure that the model logic is correct.
2. Run the simulation with one line or all lines active to see in the animation whether the right trains are covering the right lines.
3. For each line verify, that the cycle time (the time it takes to run one round starting at a random station and ending at the same station) is correct. This test is performed with constant running

and dwell times and with added delay and the possibility to gain at stations by using minimum dwell times or by gaining at the end station by using minimum shunting time. This verifies that the running and dwell times are correct and that the trains can gain time correctly at stations and while shunting at the end station.

4. Verify that the trains on all lines are stopping at the right stations. Also that the dwell and running times are correct according to the timetable. This is done by sending one train through the system and then examine the output file to verify the stopping pattern, the dwell times and the running times. This is repeated for all the lines.

By making these four test in the given order small errors are found in the first cases. The last case is more time consuming but the only one that verifies the model in details.

19 Development of timetables for experiments

When experimenting with robustness in timetables several timetables with different features are necessary. Different features are number of lines, stopping patterns, line structure, cycle time, homogeneous use of the double tracks, homogeneous scheduled headways and buffer times at end stations. Each timetable used in the experiments in this project has some of these specific characteristics which all relate to robustness and customer service level. In all the timetables every line are departing with a frequency of 20 minutes. The timetables are partly developed by DSB S-tog and partly constructed for this project. The overall timetables used in the experiments are:

- Actual timetable for 2006 (9 lines) developed by DSB S-tog
- Actual timetable from 2003 (10 lines) developed by DSB S-tog
- Proposed timetable with 10 lines developed by DSB S-tog
- Proposed timetable with 11 lines partly developed by DSB S-tog
- Proposed timetable with 12 lines partly developed by DSB S-tog
- Constructed timetable with 20 lines including a circular line in the central section
- Constructed timetable with 17 lines and a combination of circular line and drive-through lines in the central section.

These timetables and modifications of them will be examined thoroughly in the following sections. All the modifications are made specifically for this project.

19.0.1 Timetable from 2003

The actual timetable for 2003 with 10 lines is developed by DSB S-tog and was used in 2003. It is very similar to the normal timetable in 2005. The timetable for 2003 is included in the experiments to analyse the current situation. This timetable was the first data received from DSB S-tog and the Arena model is build based on this timetable. The line plan of the 2003 timetable is shown in Figure 50.

In the real system line Ex is inserted in Køge, drive to Hellerup and is taken out at København. A version of the timetable from 2003 has been developed where line Ex is taken out in København, to examine the situation in the real world system.

In the general plan from 2003 used in this project line Ex is augmented from København to Køge to make line Ex circular. In reality only four departures for line Ex exist during the day. These four departures are in the morning rush hour. In this project line Ex is run continually, because the purpose is to examine a worst case situation.

A version of the 2003 timetable with a more homogeneous distribution of the tracks at København has also been developed and implemented. In København there are two tracks in each direction. The

Figure 50: The S-trains line plan for 2003

timetable consists of 10 lines going through the central area in each 20 minute time segment, so the distribution of tracks at København can easily be made very homogeneous i.e. every second train use one of the tracks and the rest of the trains use the other track. This variation is expected to have a positive effect on the robustness without affecting the customer service.

A fourth edition of the timetable from 2003 has also been constructed where lines with small buffer times have been given larger buffers.

19.0.2 Timetable for 2006

The actual timetable for 2006 is included to investigate the proposed situation for next year, but also to examine the effect of running only 9 lines. Figure 51 displays the line plan for 2006. The timetable for 2006 is very similar to the timetable from 2003 except that line Bx is cancelled in the plan for 2006 and line A^+ terminates in Buddinge instead of terminating at Østerport. As in the plan from 2003 line Ex is augmented from København to Køge in the timetable for 2006, to make line Ex circular.

Another version where line Ex is taken out in København has also been developed and implemented to investigate the situation in the real world system.

19.0.3 Timetable with 10 lines and homogeneous line structure

A new timetable with 10 lines has been proposed by DSB S-tog, and is included in this project to investigate a timetable which is somewhat similar to the timetable from 2003 but with more homogeneous running patterns and cycle times. Homogeneous means that similar lines have the same stopping patterns and that the difference between the longest and shortest cycle time is smaller. This smaller difference has been achieved by letting lines A and A^+ run from Farum to Hundige, instead of from Hillerød to Hundige and from Hillerød to Køge. Line H is terminating at Østerport instead of running all the way to Farum which also gives a shorter cycle time. In the timetable for 2003, the longest cycle time is defined by the series from Frederikssund to Farum. This series is split between lines in this timetable, which makes the longest cycle time smaller. To improve the customer service level the former line Bx is extended and terminates in Farum, and is renamed to line Dx. The line plan is shown in Figure 52.

An additional version of the proposed timetable with 10 lines has been developed, where line Dx is modified such that it terminates in Buddinge. This has been done to make the proposed timetable more similar to the plan from 2003, which also has 10 lines, including 3 lines to Høje Taastrup and only 2 lines to Farum, to possibly get more comparable results.

This additional version has been modified further in a final version where buffer times at the terminals are improved.

19.0.4 Timetables with 11 and 12 lines

To analyse the effect of running more than 10 lines in the system, two different timetables with 11 and 12 lines are developed and examined. In these timetables with 11 and 12 lines all the lines are covered with a 20 minutes interval as normally. This means that more lines result in more departures. Running more lines in the system is therefore assumed to have a negative effect on the robustness of the plan, but at the same time the customer service is improved since there are more departures in each time segment. In the plan with 12 lines there are no fast lines, so the travel times should also increase, but the waiting time should decrease because the number of departures in each time segment increase.

DSB S-tog have drafts of timetables with respectively 11 and 12 lines, but they have never been used. In the data received from DSB S-tog some of the lines arrive at København (and the central area) one minute apart, which is not realistic with minimum 1.5 minute safe headways and certainly not robust. Both timetables are modified according to the minimum headways.

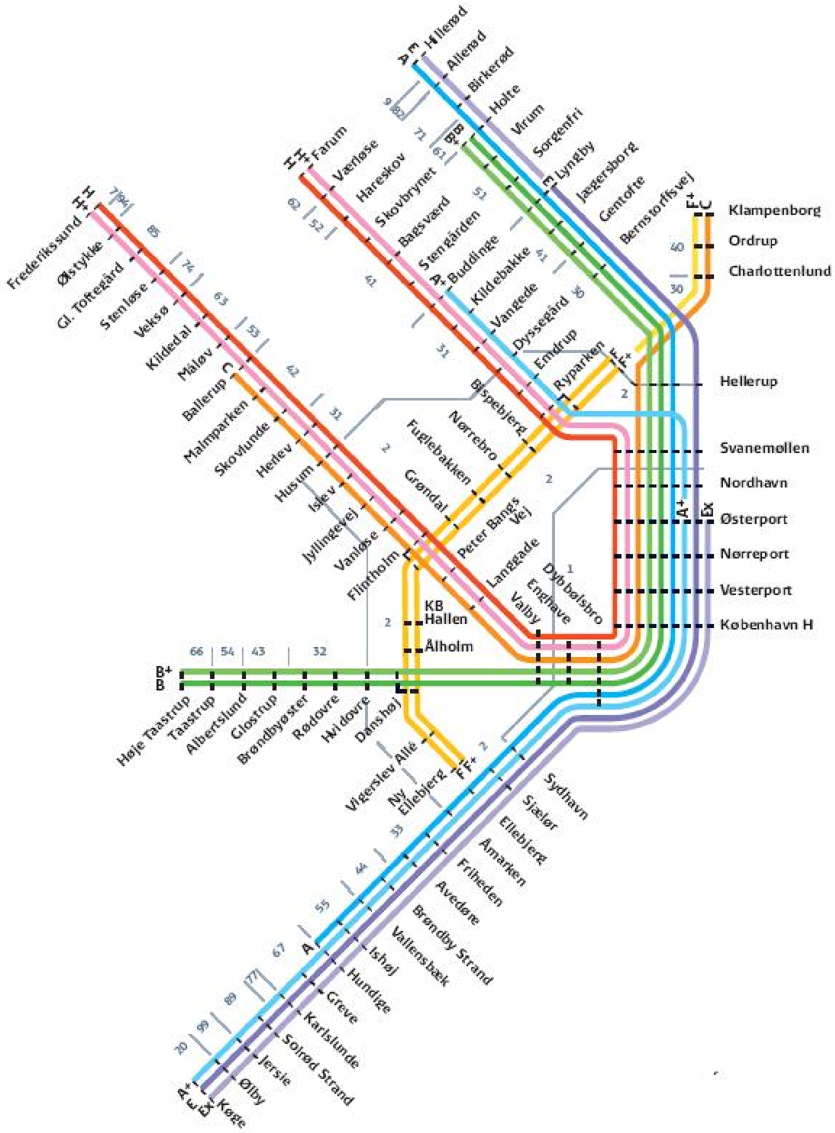


Figure 51: The S-trains line plan for 2006

Figure 52: The proposed line plan with 10 lines

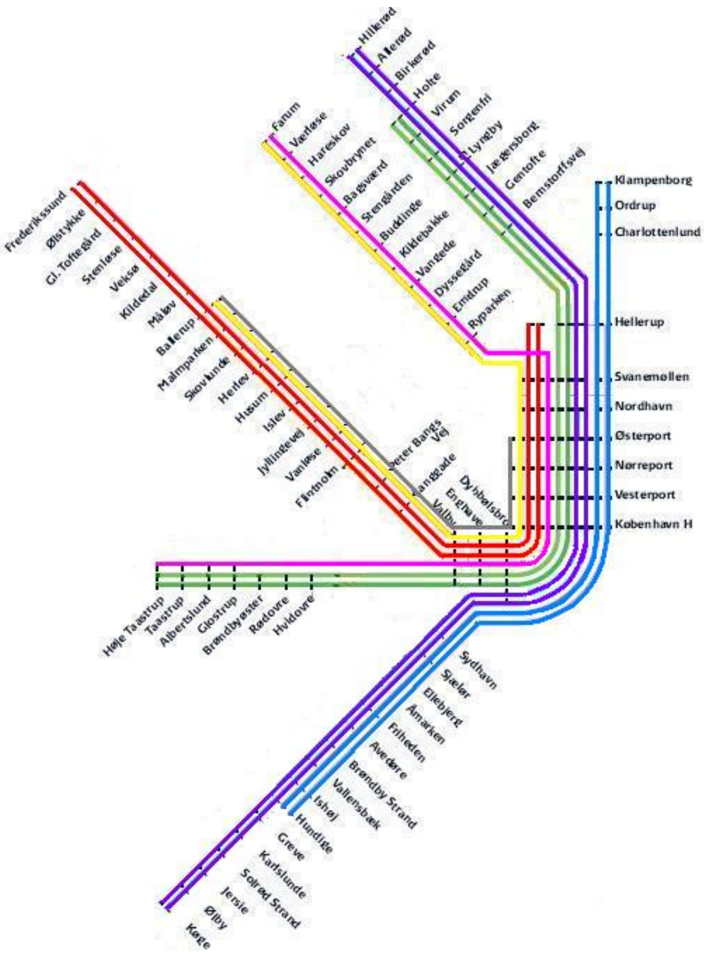


Figure 53: Line plan for the timetable with 11 lines

The structure of the timetable with 11 lines is somewhat similar to the current situation, with the exception of a line between Klampenborg and Hundige and one between Farum and Høje Taastrup. Furthermore the lines from Frederikssund terminate in Hellerup and the line from Ballerup terminates in Farum instead of Klampenborg in the timetable with 11 lines. The lines of the timetable with 11 lines are shown in Table 10 and Figure 53.

The structure in the proposed timetable with 12 lines is very different from the current situation. The line plan is shown in Figure 54 and the line description is given in Table 11. The lines are divided into 3 groups of 4 identical lines, which makes the timetable as homogeneous as possible with regards to homogeneous stopping patterns. The homogeneity is supposed to improve the robustness of the plan. Lines A, A^+, Ax and Axx all run the same series and have the same stopping patterns, and are run with 5 minute intervals. Similarly for lines B, B^+, Bx and Bxx, as well as for lines C, C^+, Cx and Cxx. The A lines cover the series from Farum to Høje Taastrup, the B lines run from Køge to Hillerød

Lines	End stations	color
A A^+	Klampenborg, Hundige	light blue
B B^+	Holte, Høje Taastrup	green
C	Ballerup, Farum	yellow
C^+	Ballerup, Østerport	grey
D^+	Høje Taastrup, Farum	pink
E E^+	Hillerød, Køge	purple
F F^+	Hellerup, Frederikssund	red

Table 10: The lines for the timetable with 11 lines

and the C lines run from Frederikssund to Klampenborg. In the plan the x-lines represent lines during daily hours and the xx-lines represent the rush hour lines. In the plan the lines are distributed such that when the x-lines and xx-lines are taken out the buffer times are equally distributed in the central section, see appendix I for the departure times for the 12 lines. In the experiments all lines are run continually to test a worst case scenario.

Lines	End stations	color
A A^+ Ax Axx	Hillerød, Køge	blue
B B^+ Bx Bxx	Farum, Høje Taastrup	green
C C^+ Cx Cxx	Klampenborg, Frederikssund	red

Table 11: The terminals for the 12 lines in the timetable

3 alternative versions of the proposed timetable with 12 lines have been developed. One where the tracks at København are distributed such that every other line arriving at København alternate between the 2 tracks (In the original version lines A and C use one track and line B the other, and in the alternative version all normal lines and +-lines use one track and all x- and xx-lines use the other). In the second version extra trains have been used such that no lines need to merge. This results in improved buffer times for some, but not all lines. In the final version lines have been merged in another way compared to the original version, which results in improved buffer times for all lines.

19.0.5 Circular timetable and a combination of circular and normal timetable

To examine a line plan totally different from the one in the current timetable two alternative timetables are developed for the experiments; a timetable with a circular line in the central section and a timetable which is a combination of the current timetable and the circular timetable. The idea with the circular timetable is that no lines go from the northern part of the network through the central area and down to the southern part or opposite. The train lines are running in smaller circles in the northern and the southern part of the network and a separate line is covering the central area. This timetable is expected to be very robust because the lines are short and homogeneous but mostly because the lines do not intersect in the central area and thereby secondary delays should be minimized. In Table 12

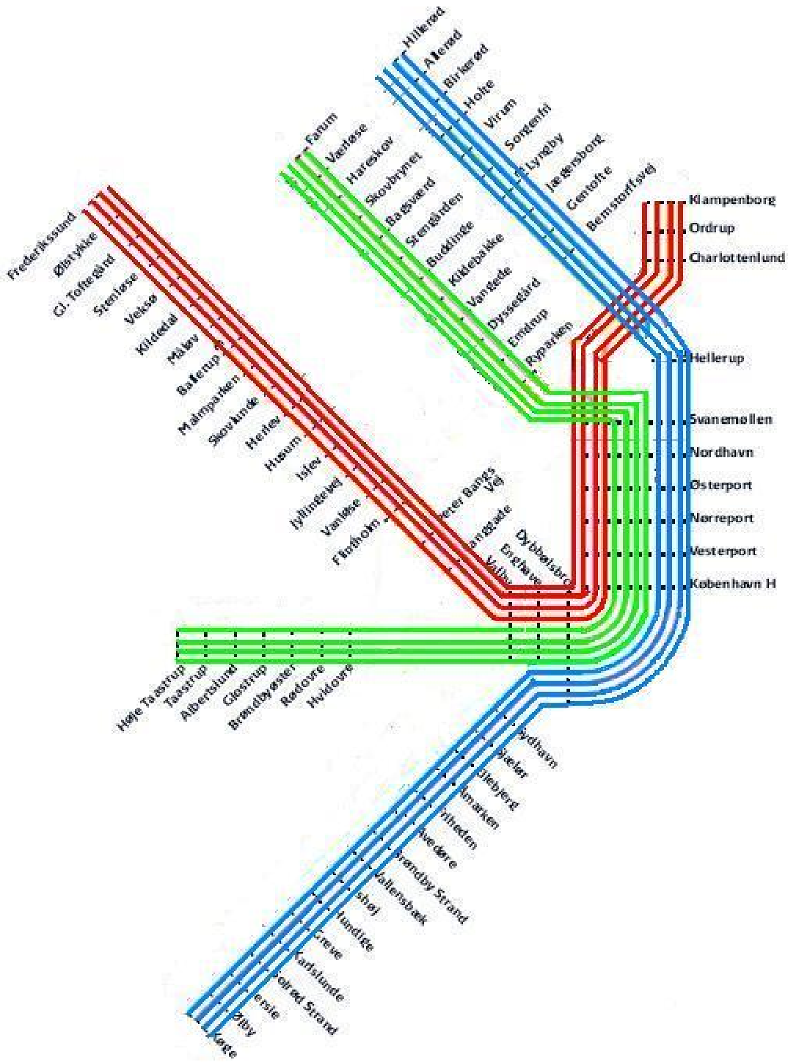


Figure 54: Line plan for the timetable with 12 lines

the 20 lines are specified and in Figure 55 the structure is shown.

Lines	**End stations**	**color**
A A^+	Hillerød, Hellerup	light blue
B B^+	Holte, Hellerup	light green
C C^+	Frederikssund, Dybbølsbro	yellow
Cx	Ballerup, Dybbølsbro	grey
D D^+ Dx	Høje Taastrup, Dybbølsbro	dark green
E E^+	Hundige, Dybbølsbro	purple
G G^+	Køge, Dybbølsbro	dark blue
H H^+ Hx	Farum, Svanemøllen	red
L L^+	Klampenborg, Hellerup	black
K	Hellerup, Dybbølsbro	pink

Table 12: The 20 lines in the circular timetable

All the lines except the central line (K) are running with a 20 minute interval as normally. The central line is running with a 2 minute interval. The idea in the central area is not necessarily to depart or arrive according to a given timetable but to maintain regular headways by having a departure every second minute. The circular timetable is developed with the proposed timetable with 10 lines as a basis. The 19 lines not covering the central area are constructed by copying parts of the timetable with 10 lines. As an example the lines B/B^+ and D/D^+ in the circular timetable are constructed respectively of the northern and the southern part of lines B/B^+ in the proposed timetable with 10 lines. In a similar way the other 15 lines in the circular timetable are created. The central line is constructed with one of the 10 lines from the original timetable as basis, but departing every second minute. The central line is totally independent from the other 19 lines, because it does not share any track with the other lines. All the joint stations (Hellerup, Svanemøllen and Dybbølsbro) have double tracks which are split between the central line and the other 19 lines.

Intuitively the customer service level for the circular timetable is low compared to the current timetables, since no trains are going from north to south or the other way to cover the long trips. If a passenger wants to travel from e.g. north to south two changeovers are necessary as opposed to the current situation where a maximum of one changeover is necessary. This should result in longer travel times, but since the circular line in the central section departs every second minute, the overall travel times should not increase significantly. On the other hand the structure of the timetables should ensure a high robustness and a high regularity which will improve the customer service level.

The combination of the circular line plan and a plan similar to the current situation is also based on the proposed timetable with 10 lines. The combination timetable has 17 lines which are a combination of the short lines in the circular timetable and longer lines going through the central area. Still no lines are going all the way from north to south or opposite. 10 lines are going through the central area and 7 lines are driving either from north or south to the central area. The line description is seen in Table 13 and the line structure is seen in Figure 56.

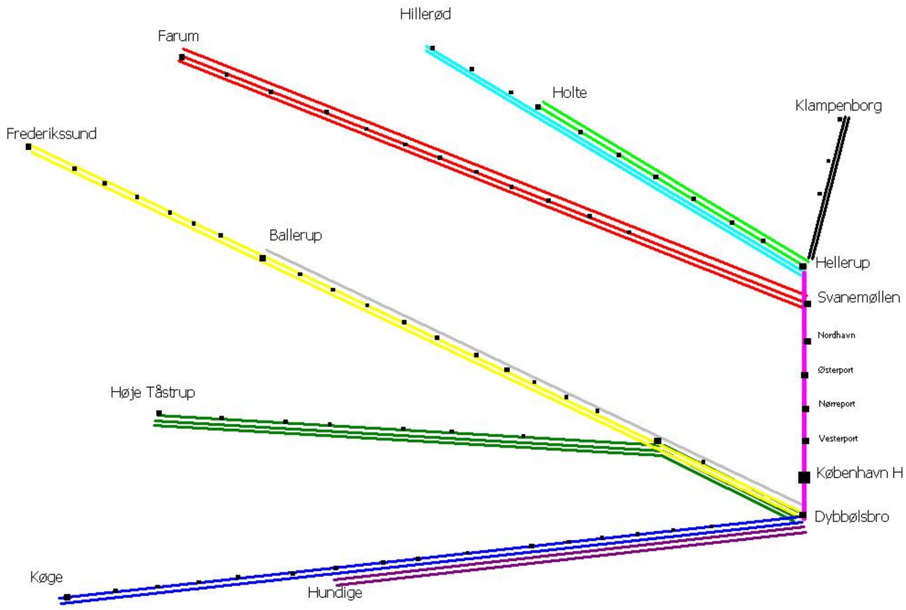


Figure 55: Line plan for the circular timetable

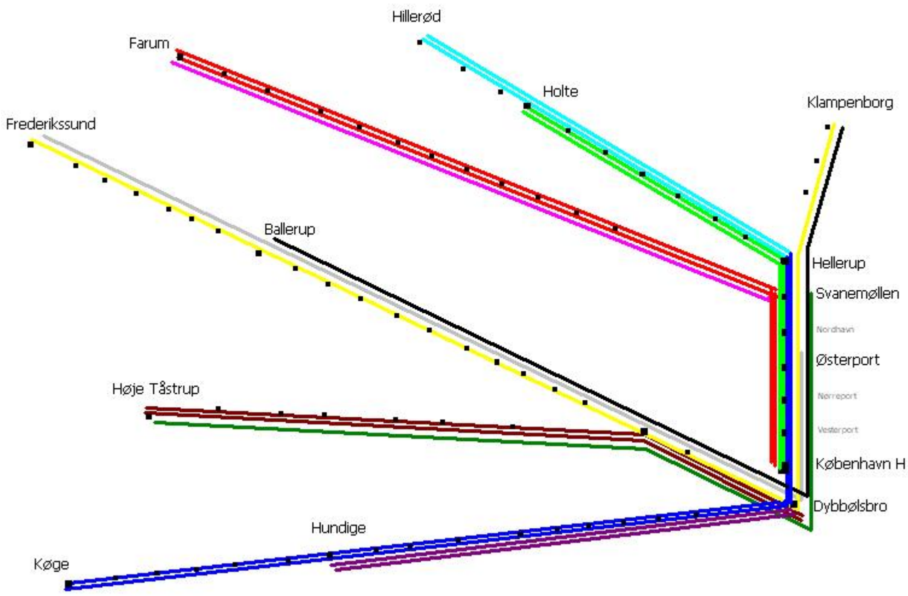


Figure 56: Line plan for timetable with 17 lines

Lines	End stations	color
A A^+	Hillerød, Hellerup	light blue
B B^+	Holte, København	light green
C	Ballerup, Klampenborg	black
C^+	Frederikssund, Klampenborg	yellow
Cx	Frederikssund, Østerport	grey
D D^+	Høje Taastrup, Dybbølsbro	brown
Dx	Høje Taastrup, Svanemøllen	dark green
E E^+	Hundige, Dybbølsbro	purple
G G^+	Køge, Hellerup	dark blue
H H^+	Farum, København	red
Hx	Farum, Svanemøllen	pink

Table 13: The 17 lines in the combination timetable

The main idea with the combination timetable is to have some lines going through the central area to meet customer satisfaction while still having lines in smaller circles outside the central area to minimize the secondary delays. A timetable with a structure like the combination timetable could be a good way of constructing a timetable which is optimal with concern to both robustness and customer service level.

An improved version of the combination timetable has also been developed, where extra trains have been used to give lines with small buffer times at the terminals better buffers to investigate the effect on the robustness.

The circular and combination timetables are not necessarily directly compatible with the current structure of the S-train network. Svanemøllen and Dybbølsbro may not be possible terminal stations in the current network and concerns regarding e.g. signals, personnel and maintenance of trains are not considered. The timetables are thought of as prototypes and general ideas to be tested to examine a situation which is totally different from the current situation. As opposed to the timetables with more than 10 lines these two significantly different timetables are expected to be more robust than the timetables similar to the current timetable. The objective of these two experiments is to evaluate how much the robustness is improved.

19.1 General procedure when developing and implementing a timetable

A timetable received from DSB S-tog consists of nothing but departure times. Several other properties are necessary for simulating a timetable. The general procedure of developing and implementing timetables in Arena is time consuming, because it consists of many phases and has to be tested thoroughly. The different phases are:

- Calculation of running times

- Determination of buffer times
- Calculation of number of trains necessary to cover the scheduled departures
- Definition of sequences and sequence lengths
- Definition of station types for each line
- Implementation in Arena
- Verification.

All data are calculated using Excel. Examples of data representations are seen in appendix F to I. All data can be seen by viewing the enclosed CD-rom.

With given departure times and dwell times the running time between two neighbouring stations A and B can be calculated as $departure(B)$ minus $departure(A)$ minus $dwell(B)$. An example is given in the following table. The line has to depart from Nordhavn in the 14'th minute, and departs from the previous station Østerport in the 12'th minute, i.e. the difference is 2 minutes or 120 seconds. When the dwell time at Nordhavn, which is 10 seconds, is subtracted the total running time from Østerport to Nordhavn is 110 seconds. Dwell and running times are seen in appendix D and E.

Station	**Departure minute**	**Dwell time**	**Running time**
Østerport	12	30 sec.	-
Nordhavn	14	10 sec.	110 sec.

Table 14: Calculation of running times

Shunting time is defined by the arrival and departure times at the end stations on a line. The shunting time depends on three factors; the time the train arrives at the end station according to schedule, the time the train can leave the end station in the other direction according to schedule and the minimum shunting time at the particular end station. When constructing the timetable the buffer time at the end stations is minimized in order to minimize the overall use of trains, but shunting times still need to be larger than minimum shunting times. A way of minimizing buffer times is to merge two lines at shared end stations.

If the train is late when it reaches the end station the shunting time can be reduced by using the buffer time specific for the station. The buffer time is calculated as scheduled shunting time minus minimum shunting time at the particular station. Note that trains are not allowed to depart earlier than scheduled in the model.

When the dwell times are given and the running and shunting times are determined the cycle time for each line is known. The cycle time for a line is always dividable by 20 if no merging between lines occur, because the timetables are constructed to maintain a frequency of 20 minutes on the lines. Since trains are scheduled to arrive at stations with a 20 minutes interval the number of trains needed to cover a line is given by cycle time divided by 20. For example if the cycle time for a line is 160 minutes then 8 trains are necessary to cover the line. It is very important to create the correct number of trains for each line. If a smaller number of trains are created a gap of more than 20 minutes between the first and the last inserted train will exist. Opposite if more trains than needed are inserted the first and the last inserted train will arrive at stations at the same time, which is not permitted. In the case where two lines are merging the cycle time may not be dividable by 20, but by 10. The B and B^+-trains are merged e.g. in the timetable used in 2003. The cycle time is 130 minutes for both lines which results in 6 B-trains and 7 B^+-trains or 7 B-trains and 6 B^+-trains needed.

For each line in the timetable a sequence of stations is defined. A sequence for a specific line is all the stations the train covering that line is passing (stopping or not). An example of a sequences is seen in appendix G. The sequence length is the number of stations in a sequence. The double tracks at some stations are distributed between all the train lines. The distribution of the double tracks is done according to the line structures, e.g. the double tracks at Dybbølsbro station in the northern direction is split between the lines from Sydhavn and the lines coming from Enghave. Similarly with the double tracks at Valby north, Hellerup and Svanemøllen. The distribution of the double tracks at København is different. Because all the lines have the same conditions at this station, no natural splitting exists. The double tracks at København can be split to obtain maximal headways at both track or with concern of customer satisfaction i.e. letting similar lines such as A/A^+ use the same track/platforms.

To specify whether a line is scheduled to stop at a particular station in the sequence, station types specific for each line are defined. The station type is set to 1 to specify that the line is scheduled to stop on this particular station, and 3 if not. Station type 2 indicates the end stations for the particular line. The running time can only be reduced at the end stations, therefore a specific station type for end stations is used. In appendix F an example of station types is shown.

Implementing a new timetable in Arena requires that many of the variables are changed according to value and dimension. The values depend on the timetable and the dimensions mostly depend on the number of lines or sequence lengths. The new values (running times, sequences etc.) are either read directly from Excel when the simulation is running or copied manually. In addition some modules in the model should be changed or added to match the timetable. Other amounts of trains might be necessary to cover the lines, depending on the cycle times for the lines and the number of lines. If lines are merged this feature must also be adjusted in the model. Finally the recovery methods must be adapted to match the new timetable.

Finally the Arena model matching the new timetable is tested thoroughly to verify that it is running as intended. This is done by repeating the tests of the entire final model and parts of the tests of the recovery methods.

20 Experiments

In the following chapters the experiments with the different timetables are presented and analyzed. The timetables are described in chapter 19. Experiments will be made with the main timetables and with the modified versions. The experiments concern evaluation of the recovery methods and comparison of the timetables. Furthermore the following hypotheses will be examined throughout these chapters.

- Secondary delays have a significant negative effect on regularity.
- Average delay and regularity are linearly dependent.
- Larger buffers at the end stations have a positive effect on regularity and robustness.
- A more homogeneous timetable with regards to stopping patterns, will result in a higher robustness.
- Even distribution of the tracks on København station will result in more robust timetables.
- More lines in a timetable result in a lower regularity.
- A timetable with 12 lines and a frequency of 20 minutes will increase the customer service level and might be possible without decreasing the stability of the system.
- A new network pattern where lines are split into northern lines, southern lines and shuttle service in the central part of the network will result in a more robust timetable (circular timetable).
- A timetable similar to the circular timetable, but with some lines running through the central section before turning, called the combination timetable, will result in higher regularity.

In this chapter some introductions to fundamental conditions for the experiment are given. In chapter 21 the results from the experiments with the individual timetables are reviewed. All the different timetables are simulated with and without use of recovery methods. In chapter 21 the main objective is to examine the effect of the three recovery methods on the different timetables. Chapter 22 presents the results from additional experiments with delay and with buffer time at the end stations. In chapter 23 all the different timetables are compared. The main objective of chapter 23 is to examine what effect more lines, different line structures and buffer time have on regularity and robustness. Finally in chapter 24 overall conclusions on all the experiment will be given. The results that are evaluated but not presented in the chapters are given in appendix J.

20.1 Introduction

All experiments will be run for 12.5 hours from 6:00 to 18:30 i.e. 750 minutes, since this is approximately the period of time when all lines (except x-lines) are running in the network in the real system. Due to the insertion time of all the trains, the simulation time will actually be 1000 minutes. There is a 250 minute warm up period before all trains are actually running in the system. All lines will be run continually, even though the x-lines are cancelled outside rush hour in the real world situation. This is done to test the worst case robustness of the different plans. Note that the simulation time is in minutes, i.e. when referring to 'time' in the experiments or in figures, the unit is minutes. In the results from the experiments the warm up period is never considered. This means that regularity, reliability and average delay are measured after the warm up period. Furthermore the time on the x-axes in figures starting at 0 minutes is after the warm up period of 250 minutes.

In section 17.8 it is described how delay for each stations is calculated from historical data. Delay for each station is given by a distribution. In the experiments there will be 50% probability of delays occurring at each station. 50% probability of delays means that approximately every second time a train enters a station, delay is added according to the distribution of delay for the particular station.

As explained delays are drawn from a distribution and therefore 5 independent statistically identical simulations are run, to reduce the effect of outlying random values. An experiment with 10 replications was made and there were no considerable differences in the mean values, therefore 5 replications is considered sufficient. Only the mean value taken from the 5 replications is considered in the experiments. Mean regularity, mean reliability and average delay occurring for the trains are recorded for each experiment. In experiments with recovery methods the numbers of affected trains are also recorded. These values might be non-integral since they are average values from the 5 replications.

To broaden the level of comparison in the experiments the timetables are simulated with and without use of recovery method. The test cases for each timetable are:

1. With delays, but without recovery
2. With delays and recovery method Take out
3. With delays and recovery method Turn around
4. With delays and recovery method Replace.

In the experiments the following measures of robustness are used:

1. Regularity (percentage of trains running on time)
2. Average delay
3. Reliability (number of planned departures compared to actual number of departures)
4. Number of affected trains (replaced, turned or cancelled).

In principle high robustness is indicated by a stable regularity. Furthermore in this context high regularity indicates high robustness. A high regularity and few affected trains also indicates high robustness.

20.2 Fundamental conditions for the experiments

The data used for the experiments consists of several timetables with different features. Using simulation these different timetables can be compared with respect to robustness, but many factors should be considered while making this comparison.

The number of lines is an important factor when examining the robustness of a timetable, but there are also other factors which should be considered. Number of trains necessary for running the plan and buffer times at the end stations have a big influence on robustness. In Table 15 the minimum, maximum and average buffer times (in minutes) at the end stations and the trains needed to cover the scheduled departures in the timetable are listed for the different timetables. A timetable is assumed robust if it has large average buffer times at the terminal stations, but larger buffer times at terminal stations results in a larger number of trains necessary to cover the timetable. Seen from an economical point of view the fewer trains needed the better. The optimal solution is a robust timetable with as few trains as possible.

Some of the timetables constructed by DSB S-tog are made with different running times, because new trains have made it possible to run faster. With faster running times fewer trains can cover the timetable. This makes the possibility of comparing timetables according to necessary number of trains somewhat more difficult. An exact comparison on the basis of number of trains needed is therefore only possible when modifications of the particular timetables are made.

In the results it should be accounted for that not all lines have the same departure times in each plan. Therefore some variability can occur in the results even though two timetables seem to be similar. As an example the line Ex has different departure times in the plan for 2003 (10 lines) and 2006 (9 lines), which results in line Ex departing from København differently for each of the two timetables, which again results in line Ex following lines E and A^+ respectively on the route from København to Køge. In this example line Ex is affected by secondary delays from different trains which has an effect on the overall robustness. Generally the construction of the timetables has a big influence on the robustness. The order of the lines in the central area where most secondary delay occur is different from plan to plan and therefore complicates the comparison.

The main problem when comparing the different timetables is that only one or two of each type (number of lines or structure) are represented in the experiments. This makes the basis of comparison more uncertain and the possibility of generalizing the results difficult, but it is still possible to give an overall comparison by taking these issues into consideration.

Timetable	**Average buffer time**	**Min. buffer time**	**Max. buffer time**	**Number of trains needed**
2006 (9 lines)	7.2	0.5	19.2	70
2006 (9 lines) - line Ex taken out at København	7.2	0.5	19.2	70
2003 (10 lines)	6.4	0.5	14.8	73
2003 (10 lines) - line Ex taken out at København	6.4	0.5	14.8	73
2003 (10 lines) with more buffer at end stations	10.4	3.8	22.7	77
10 lines	5.3	0.2	13.3	68
10 lines - line Dx terminating in Buddinge	5.4	0.2	13.3	67
10 lines - line Dx terminating in Buddinge and improved buffer times	9.4	2.6	20.6	71
11 lines	7.1	2.1	20.1	74
12 lines	2.3	1.1	3.1	93
12 lines - no lines merging	8.1	1.1	18.1	100
12 lines improved buffer times	7.3	6.1	8.1	99
Circle	4.7	0.6	11.6	85
Combination	6.6	0.6	16.2	82
Combination - improved buffer times	8.2	2.3	21.9	88

Table 15: Experiment with delays

21 Experiments with recovery methods for individual timetables

In this section the results from the experiments with the individual timetables are reviewed. All the different timetables are simulated with and without use of recovery methods. The experiments show how the three recovery methods affect the different timetables.

Generally the results show that a higher number of lines in the timetable cause lower regularities and larger average delays.

When the overall regularity is low, the recovery method Take out turns out to give the best results. This was also expected since cancellation of entire lines is a more drastic approach for creating larger buffer times and thereby eliminating delays. When the overall regularity is relatively high, the recovery method Turn around results in the highest regularities. This is a consequence of the recovery method Turn around being activated when a single train is sufficiently late, whereas Take out is activated when the line regularity descends below a threshold of e.g. 0.90. The effect of the recovery method Replace is more limited than the effect of Turn around since trains can only be replaced at København, as opposed to being turned at all larger stations. On the other hand the reliability is much better when using the recovery method Replace since no scheduled departures are cancelled. In the following the experiments and results will be presented in more details.

Activation of the recovery methods depends on how late the trains are. The recovery methods Turn around and Replace are both activated at the following three thresholds:

1) If the train is more than 2.5 minutes late

2) If the train is more than 5 minutes late

3) If the train is more late than it can gain by using buffer time at the end station.

A train is considered late when it is delayed more than 2.5 minutes. The reason for using the threshold of 5 minutes in addition, is that it is a bigger disturbance seen from a passengers perspective. Furthermore trains covering similar lines are arriving at the stations with 10 minutes intervals, therefore 5 minutes is chosen as a threshold, because it is half the time before the next train will arrive. Finally the possibility of recovering if the train cannot gain the delayed time at the end station is a very realistic measure, since then all trains will start new trips from the end stations on time and secondary delay in the direction towards the central area should be minimized.

The recovery method Take out is activated when the total regularity decrease below 95%. As an example a line e.g. A^+ is taken out if the regularity on that particular line, or the corresponding normal line (line A), is less than the given threshold for a fixed period of time. Experiment are run with the following thresholds:

a) Regularity below 80% on the line

b) Regularity below 90% on the line

c) Regularity below 90% on the line and lines put back when total regularity rises above 95%.

In total this results in 10 different cases, with and without use of recovery methods, for each experiment with the timetables.

Results from the experiments with the proposed circular timetable are omitted in this chapter since it is irrelevant to compare different recovery methods for this timetable because it is totally different from the timetables the recovery methods are constructed for.

21.1 Timetable from 2003 (10 lines)

The results from the experiments with the actual timetable from 2003 will be explored thoroughly, to examine the effect of the three recovery methods and the different thresholds. Results from experiments with the other timetables are similar in most cases.

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	0.85	92.80	100	
Take out (a)	0.79	93.76	99.90	1 line cancelled
Take out (b)	0.70	94.93	89.69	Max. 4 lines cancelled
Take out (c)	0.70	94.75	90.75	Max. 4 lines cancelled
Turn around (1)	0.64	97.12	93.44	57.4 trains turned
Turn around (2)	0.76	94.27	98.91	9.0 trains turned
Turn around (3)	0.75	93.04	94.15	63.0 trains turned
Replace (1)	0.73	94.76	100	22.4 trains replaced
Replace (2)	0.79	93.34	100	3 trains replaced
Replace (3)	0.82	93.33	100	32.20 trains replaced

Table 16: Results from experiments with timetable 2003

Results from the experiments with the actual timetable from 2003 are given in Table 16. The results from the experiments with the recovery method Turn around show that when trains are turned when delayed more than 2.5 minutes instead of at more than 5 minutes lateness, obviously the average delay is smaller. The regularity is naturally also higher when the trains are turned earlier. Generally the expected relationship between average delay and regularity is seen; small average delay results in high regularity. The reliability is lower in the first case compared to the second case of Turn around, because fewer trains reach all their planned destinations when they are turned at a station prior to the terminal. The same results can be seen when trains are replaced when they are more than 2.5 minutes late compared to the case where they are replaced when they are more than 5 minutes late.

The results where trains are turned or replaced if the delay increases above the time that can be gained by using the buffer times, are of interest. This should reduce the secondary delays propagating because trains should run on time when a new trip from a terminal is started. If the delay has reached the limit where the train no longer is certain to run on time on the next trip, the recovery method is activated. Depending on the average buffer time at the terminal station, meaning how much can be gained at the end stations, this threshold gives better or worse results that by using 2.5 or 5 minutes delay as threshold. Activating the recovery method when the train is more late than it can possibly gain at the end station should be the most realistic solution, because there is no reason to use a recovery method if the delay can be eliminated by using buffer times. In the real world a combination of the three thresholds is probably used.

In the experiments with the recovery method Take out it is seen, that when the threshold for the regularity on lines is set to 80% below which lines are taken out, the results for average delay and regularity are worse than the situation where the threshold is set to 90%. This is not surprising since trains with delays are kept longer in the system, in the first case, before they are taken out and therefore affect the average delay and the regularity for a longer time. On the other hand keeping the trains in the system longer has a positive effect on the reliability, and therefore the reliability is higher in the first case.

Naturally it can be seen from the results that when the reliability decrease the regularity increase. Less trains running will result in more buffer times between trains which decreases the risk of secondary delays. Thereby the possibility of getting a better regularity increases.

Comparing the results for Take out (b) and Take out (c) it can be seen that the regularity is a little bit higher and the reliability a little smaller when lines are not re-inserted (case b). The reason is that when lines are re-inserted they increase the reliability on the line and the overall regularity decreases, because there are more trains running in the system.

The recovery method Turn around gives the highest regularity in the experiments with the timetable from 2003. The reason for this is that the regularity is reasonably high in the case where no recovery method is applied. If the regularity was low in the case with no recovery, Take out would intuitively turn out to be the best recovery method since this is a more drastic approach. The recovery method Replace is not expected to be the best regarding regularity, since the recovery only takes place at one station (København) as opposed to the other two recovery methods. When using Replace the reliability is 100% no matter how many trains are replaced at København station. Naturally the passengers are also disturbed when a train is replaced, but only the passengers in the train, not the passengers waiting on the stations, since no departures are cancelled.

An additional experiment is made with the timetable from 2003. Instead of having line Ex running continually between Køge and Østerport, the line starts in Køge, goes to Østerport and ends in København where it is taken out. This is the actual structure of the plan for 2003. The experiment results in a average regularity of 94.78%, which is a general improvement of 0.6 percentage points.

21.2 Timetable for 2006 (9 lines)

The results from the experiments with the actual timetable for 2006, shown in appendix J, are generally very good and show that the plan is very robust. This is not surprising since only 9 lines are running, which cause larger buffer times between trains. The results from the recovery methods are similar to the results found with the timetable from 2003. Again the recovery method Turn around is the best regarding regularity. Note that line Ex is augmented from København to Køge, to make the line circular.

In the experiment with Take out (c) a different number of lines are cancelled in each replication. In Table 17 the lines cancelled and their regularity when they are cancelled are shown for the 5 replications. Figure 57 shows the development in the regularity for each replication. It can be seen that the regularity is decreasing and at some point it begins to increase again. The increment happens at the time when lines are cancelled. Replication 3 (the green graph) shows the development in the regularity best, since in this replication most lines are cancelled. The reason the regularity does not increase immediately after the regularity descend below 95% is that lines are not cancelled at once but at the next depot. In replication 1 (the navy blue graph) it can be seen that when the cancelled line is re-inserted at time approximately 450 the regularity begins to decrease again.

Replication	**Line A+**	**Line Ex**	**Line H+**
1		0.82	
2		0.87	
3	0.95	0.86	0.90
4		0.87	0.90
5		0.75	

Table 17: Number of lines cancelled and regularities in experiment with Take out (c)

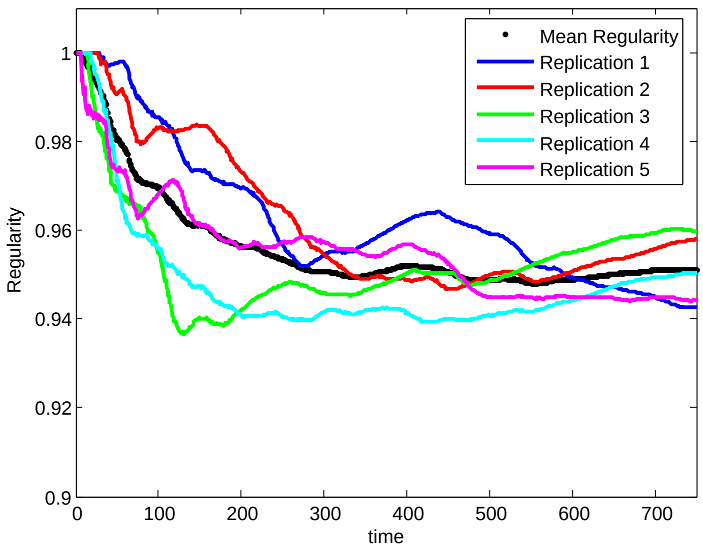


Figure 57: Development of regularity for 5 replications

Experiments are also made with the actual timetable for 2006 (9 lines) and Line Ex terminating in

København in the southern direction. Instead of having line Ex going in a circle between Køge and Østerport, the line starts in Køge, goes to Østerport and ends in København where it is taken out. It turns out that all results, with regards to regularity and average delays, are better when line Ex is taken out at København. This is not surprising since there are less trains in the system that can be disturbed and there is more buffer time between trains in the section from København to Køge when line Ex does not run this distance. Surprisingly this small change has a very positive effect on regularity. The regularity is improved with an average of 1.5 percentage points, which is a significant improvement. This result indicates that line Ex has a low regularity and therefore a considerable effect on the overall regularity. This indication is confirmed by examining the regularity on the lines specifically. In the real plan developed for 2006 line Ex does not run from København to Køge.

21.3 Proposed timetable with 10 lines

Results from the experiments with the proposed timetable with 10 lines are given in Table 18.

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	1.37	85.49	100	
Take out (a)	1.22	87.95	95.52	Max. 2 lines cancelled
Take out (b)	0.84	93.06	79.21	Max. 3 lines cancelled
Take out (c)	0.92	91.26	80.25	Max. 3 lines cancelled
Turn around (1)	0.70	96.72	94.34	56.8 trains turned
Turn around (2)	0.88	92.16	98.85	14 trains turned
Turn around (3)	0.69	95.29	84.23	111 trains turned
Replace (1)	0.83	93.80	100	43 trains replaced
Replace (2)	0.93	91.55	100	5 trains replaced
Replace (3)	0.89	92.19	100	59.4 trains replaced

Table 18: Results from experiments with proposed timetable with 10 lines

The interesting observation in these experiments is that the reliability in Turn around (1) is much better than Turn around (3), even though the regularity is lower for Turn around (3). The low regularity is a result of small buffer times in this timetable, which causes a large number of trains to be more late than they can gain at the end stations, and thereby a large number of trains are being turned. A higher regularity is reached in Turn around (1) even though fewer trains are turned. The reason for this difference can be explained by the variation of trains being turned. When turning trains which are delayed more than 2.5 minutes all trains in the network can be turned if delayed. On the contrary when the threshold depends on the buffer time, which are different for the 10 lines, only some delays can be eliminated.

As another experiment the proposed timetable with 10 lines has been modified such that line Dx terminates in Buddinge. This has been done to make the proposed timetable more similar to the plan from 2003, which also has 10 lines, including 3 lines to Høje Taastrup and only 2 lines to Farum, to possibly get more comparable results. The results from the experiments with the modified version of the timetable are shown in appendix J. The comparison of the timetable from 2003 and the proposed timetable with 10 lines will be given in chapter 23.

When comparing the results from the two experiments with the proposed timetable with 10 lines (line Dx terminating in Buddinge and Farum respectively), not surprisingly it turns out that shortening line Dx results in a better regularity. In this case the regularity only improves with an average of 0.5 percentage point, which indicates that running line Dx all the way to Farum does not influence the overall regularity much.

21.4 Combination timetable

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	0.80	93.35	100	
Take out (a)	0.77	93.77	97.95	Max 1 line cancelled
Take out (b)	0.67	95.07	86.39	Max 3 line cancelled
Replace (1)	0.68	95.50	100	15 trains replaced
Replace (2)	0.70	94.90	100	3 trains replaced
Replace (3)	0.71	94.72	100	9 trains replaced

Table 19: Results from experiments with combination timetable

In the results from the experiments with the proposed combination timetable, given in Table 19, the recovery method Replace gives the highest regularity. The regularity is considered high in the case where no recovery method is being used, and therefore the regularity cannot be improved much by cancelling lines, since this is done when the regularity gets below 95%. The recovery method Turn around is not implemented since lines are relatively short, and therefore cannot be turned before the end stations, hence it is not surprising that Replace gives the best results.

21.5 Timetable with 11 and 12 lines

The results from the experiments with the timetable with 11 lines, shown in Table 20, are generally good, considering that the timetable has an extra line. The robustness is generally on the level of the results from the experiments with the timetables with 10 lines. This indicates that not only the number of lines affect the regularity. Further comparisons of the different timetables will be made later in this chapter.

In the experiments with the timetable with 11 lines the recovery method Take out gives the highest regularities. This is a result of a lower regularity when no recovery method is used, and therefore the more drastic approach of cancelling entire lines should be the best method to obtain a high regularity. The highest regularity also gives the lowest reliability because 4 lines must be cancelled to attain the

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	1.22	86.80	100	
Take out (a)	0.82	93.67	87.30	Max 2 lines cancelled
Take out (b)	0.70	95.19	67.75	Max 4 lines cancelled
Turn around (1)	0.84	94.18	93.26	75 train turned
Turn around (2)	0.95	91.87	99.04	13 train turned
Turn around (3)	0.96	91.44	97.50	30 train turned
Replace (1)	1.02	90.47	100	26 train replaced
Replace (2)	1.09	88.91	100	9 train replaced
Replace (3)	1.08	89.32	100	23 train replaced

Table 20: Results from experiments with plan with 11 lines

high regularity.

Similarly in the experiments with the timetable with 12 lines the recovery method Take out also turns out to be the best method, if concerned about a high regularity and low average delays. The results can be seen in appendix J. Again Take out achieves the lowest reliability due to a large number of scheduled departures being cancelled in order to obtain a high regularity. In the second case where the lines are taken out if the total regularity decreases below 90%, all 6 lines possible (Ax, Axx, Bx, Bxx, Cx and Cxx) are taken out and as a result the reliability is around 50% since half the number of lines are taken out.

22 Other experiments

In this chapter additional experiments with delays are conducted. It is shown that the regularity is non-linearly decreasing when the probability of delay increases. Furthermore it is confirmed that small and large delays have very different impacts on the regularity, and more interestingly that small delays cause secondary delays when added to the large delays. In a third experiment with delays the relationship between average delay and regularity is seen to be linear.

This chapter also examines experiments with buffer times. Results from several experiments show that the amount of buffer time has a significant effect on the robustness of the timetable. More buffer time results in less recovery needed to achieve higher regularities. Furthermore it is shown that the amount of buffer time necessary to achieve a robust timetable is limited.

Last in this chapter it is confirmed that trains are waiting in queues for station and routes mainly in the central area.

22.1 Experiments with delay

The delays added in the model are given by distributions and the probability of delay is determined to fit a realistic regularity. Generally in the experiments the probability of delays occurring is set to 50. Experiments are made to examine how the probability of delay affects the regularity. Four timetables with respectively 9 lines (actual 2006), 10 lines (proposed timetable with improved buffer times), 11 and 12 lines are simulated with probability of delay set to $0, 10, 20, \ldots, 100$. All the experiments are run without recovery methods.

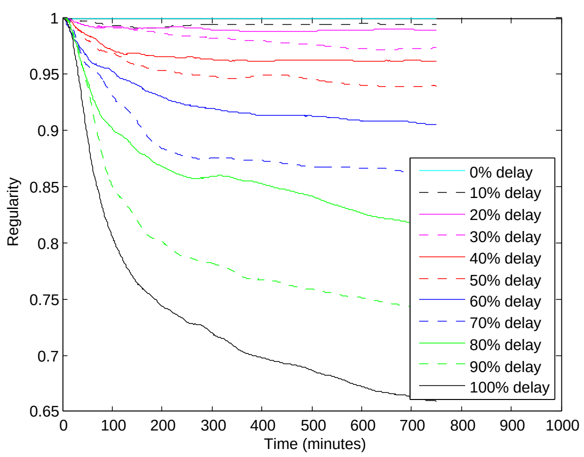


Figure 58: Regularity for the different percentage delay values

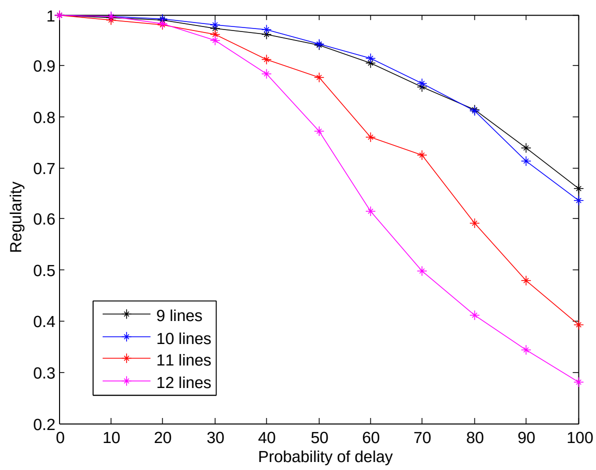


Figure 59: Regularity as a function of probability of delay for the four timetables

Figure 58 shows the regularity for the different probability values for the timetable with 9 lines. The results confirm that a lower probability of delay results in a better regularity. The results also show that this relationship is not linear. The change from probability e.g. 80% to 90% has a bigger negative effect on regularity than the change from 20% to 30% probability. Experiments with the other three timetables give the same results only with other values on the y-axes. In Figure 59 the regularity after 750 minutes are shown as a function of probability of delay for all the timetables. Here it is seen that the regularity is decreasing when the probability of delay is increasing. Note that the relationship is not linear. This relationship can be explained because of secondary delay. Naturally the delays added directly to the trains affect the regularity, but the secondary delays occurring because of the interaction between the trains also affect the regularity.

22.1.1 Large and small delays

As explained earlier the delays added in the model are determined from historical data. The distributions representing the delays are different for each station. For some stations the delays are bigger than for others as it is in the real system. To examine how small and large delays affect the regularity of the system, experiments with small and large delays are made separately. Because a definition of small and large delays is difficult to determine, the median is used. The delays are divided into the 80 stations with the smallest delays and 81 stations with the largest delays. In the experiment with smaller delays all the 81 distributions of larger delays are set to zero, meaning that no delays occur on these 81 stations. Similarly for the experiment with large delays, the distributions for the small delays are set to zero. This means that in both experiments delays are only occurring at half the stations as opposed to the experiment with all delays, where delay might occur at all the stations. The experiment with all the delays will therefore result in the lowest regularity.

Again the experiment is made with four timetables with respectively 9 lines (actual 2006), 10 lines (proposed timetable with improved buffer times), 11 and 12 lines. The experiments are run with no recovery and 100 % probability of delays. This means that at the stations where the delay distribution is not zero, delay will be added every time a train enters the station.

The results of the experiments are shown in Figure 61 and 60. The figures show the regularity for the timetables with respectively 11 and 12 lines. The results from the timetables with 9 and 10 lines show the same results and can be seen in appendix J. Experiment with the same four timetables and a percentage delay of 50% have also been conducted and results were similar. It is seen that even though the definition of small and large delays is vague the results from the experiments with large and small delays are very different. The regularity with only the large delay (the black curve) is an improvement compared to the regularity for the simulation where all delay are added, but clearly the larger delays have a negative effect on the regularity. The smaller delays have almost no effect on the regularity. The simulation with only small delays (the blue curve) gives a very good regularity close to 100% (a close-up shows that it is not exactly 100%). This can be explained by the possibility of gaining time at each station by reducing dwell time to the minimum and by gaining time at the end stations. This experiment also confirms that secondary delays have a big effect on regularity. Smaller delays alone do not affect regularity, but omitting the smaller delays gives a considerably better regularity than with all delays added. This is the effect of secondary delays.

This experiment confirms that large delays should be minimized and that a focus on larger delays is

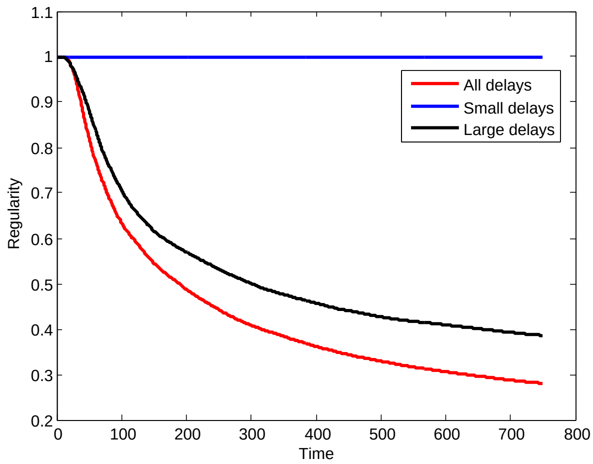


Figure 60: Timetable with 12 lines

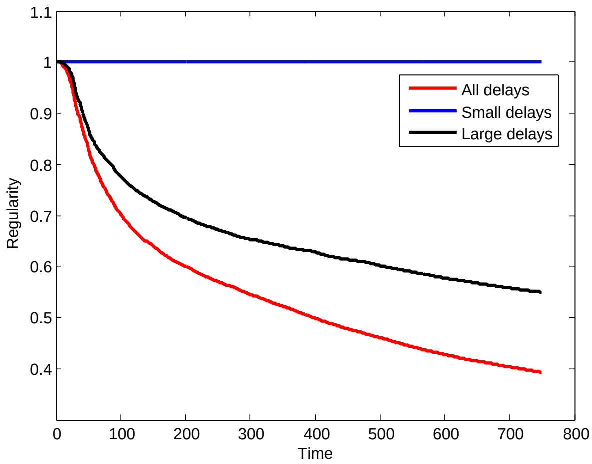


Figure 61: Timetable with 11 lines

more important that on smaller delays. On the other hand smaller delays might be easier to eliminate, which also have a significant positive effect on the regularity because of secondary delays.

The two experiments with delay examined above both show that the timetables with respectively 9, 10, 11 and 12 lines all react relatively the same, when different intensities of delays are added.

22.1.2 Relation between average delay and regularity

A relationship between average delay and regularity is made by comparing all achieved average delay and regularities. As the graph in Figure 62 shows the average delay and the regularity are linearly dependent as expected.

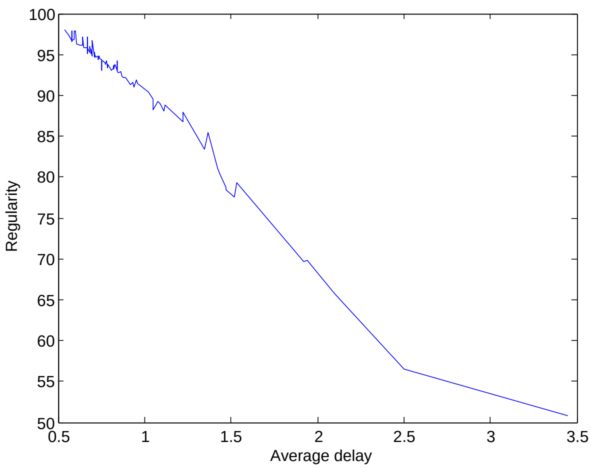


Figure 62: Average delay and regularity

22.1.3 Experiments with delays in the morning rush hour only

To examine the recovery methods when delay is added in a fixed period of time, an experiment with rush hour delay is conducted. The delay in this experiment is added with a probability of 60% for 3 hours only, from 6:00 to 9:00. This should indicate the morning rush hour where more delays occur but for a shorter period of time. The timetables examined are the timetables with 9 lines (actual 2006), 10 lines (actual 2003), 11 lines and 12 lines. The regularities of all the four timetables where no recovery is used are seen in Figure 63. Note that the vertical dotted black line indicates when rush hour ends after 180 minutes and that the horizontal dotted black indicates a regularity of 95%. The figure shows that if delay is added only in a fixed period of time the timetables with 9, 10 and 11 lines will recover and regain a regularity above 95% after respectively approximately two hours (at 300 minutes), approximately three and a half hours (at 400 minutes) and approximately five hours (at 480 minutes). The regularity for these three timetables increases just after rush hour ends. The regularity of the timetable with 12 lines increases a little later and does not reach 95%.

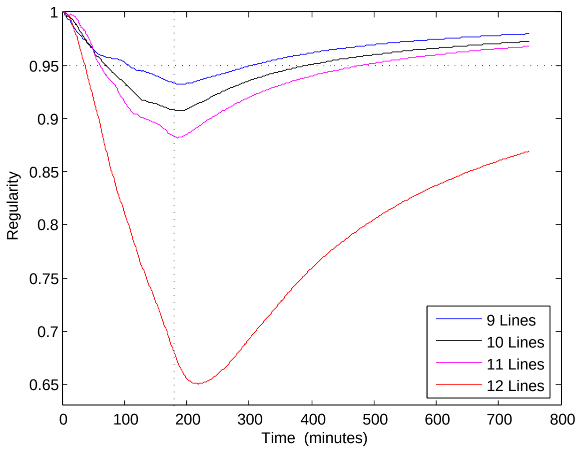


Figure 63: Experiment with rush hour delay

In the Figures 65 and 64 the same results are presented for the timetables with 11 and 12 lines. In these figures the regularity is shown when the recovery methods are used. Again the timetable with 12 lines does not obtain a regularity of 95% even though recovery is used. The recovery method where lines are taken out almost results in a regularity of 95%, but not until the end of the day. In Figure 65 it is seen that the recovery where trains are turned after being 2.5 minutes late gives the highest regularity. Taking lines out gives almost the same result. Using these recovery methods the regularity reaches 95% approximately two hours after rush hour as opposed to approximately five hours after rush hour if no recovery is used. This experiment confirms the big effect the recovery methods have on the regularity.

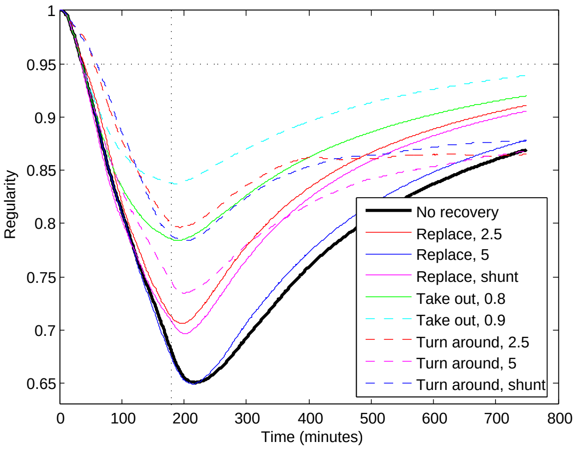


Figure 64: Timetable with 12 lines

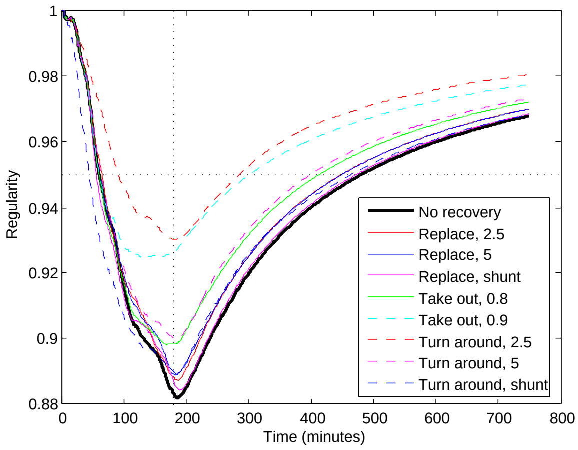


Figure 65: Timetable with 11 lines

22.2 Experiments with more buffer time at end stations

In the case where no recovery method is used in the model, delayed trains can only gain time by dwelling less time at stations or by turning faster than scheduled at the end stations. This means that the buffers in the shunting times are very important to maintain a high regularity. Therefore several experiments are made with buffer times at the end stations.

In the first experiment the actual timetable from 2003 has been modified by adding more trains which improves the buffer times at the end stations. Lines which can gain less than 3 minutes in the original plan from 2003 have been modified by inserting extra trains such that all lines can gain at least 3 minutes at both terminals. Table 21 shows the changes in the timetable.

Line	**Station**	**Buffer time in original plan**	**Buffer time in modified plan**
A^+	Østerport	2.67	22.67
Bx	Hellerup	0.83	20.83
C	Ballerup	0.50	20.50
Ex	Hellerup	0.83	20.83

Table 21: Buffer times in plans

This experiment will show the improvement in regularity, reliability and average delay when four extra trains are inserted. The results from the original and the modified timetable are shown in Table 22.

Almost all results are improved when the buffer times at the end stations are improved (except the results in bold face which are almost the same but a little worse than in the original plan). The results for Take out (a) are better in the original timetable since no lines are cancelled in the timetable with better buffer times. Note that the improved results for the recovery methods Turn around and Replace, are obtained by affecting less trains. The average improvement in the regularity is 0.3 percentage point.

Recovery	Average Delay		Regularity		Reliability		Trains affected	
	Original 2003	Modified 2003	Original 2003	Modified 2003	Original 2003	Modified 2003	Original 2003	Modified 2003
None	0.85	0.82	92.80	93.27	100	100	-	-
Take out (a)	0.79	**0.82**	93.76	**93.27**	99.90	**100**	1 line	**0**
Take out (b)	0.70	**0.74**	94.93	**94.48**	89.69	**88.65**	4 lines	4 lines
Turn around (1)	0.64	0.60	97.12	97.84	93.44	95.10	57.4	45
Turn around (2)	0.76	0.72	94.27	94.71	98.91	99.29	9	7.8
Turn around (3)	0.75	0.75	93.04	94.21	94.15	99.56	63	4.2
Replace (1)	0.73	0.71	94.76	95.21	100	100	22.4	16
Replace (2)	0.79	0.75	93.34	94.15	100	100	3	1.6
Replace (3)	0.82	0.80	93.33	93.39	100	100	32.2	0.2

Table 22: Experiments with improved buffer times for the timetable from 2003

This might be considered a small improvement for the cost of four extra trains, but less recovery has to be performed, which implies that the timetable becomes more robust when more buffer time is added. The reliability is also improved when less recovery has to be performed to maintain the scheduled plan. This implies an improvement in customer service level.

An experiment with the proposed timetable with 10 lines has also been conducted by modifying the timetable such that all lines have buffer times larger than 2.5 minutes at the end stations. The modified plan is made from the plan where line Dx terminates in Buddinge. Buffer times from the original plan and for the modified plan can be seen in Table 23 for the lines where changes have occurred.

Line	Station	Original buffer time	Modified buffer time
A and A^+	Farum	0.6	20.6
E and E^+	Hillerød	0.2	20.2

Table 23: Buffer times for experiment with improved buffer times in timetable with 10 lines

Generally the results for the modified version are better than the results from the original timetable. The results can be seen in appendix J. An average of 5.4 trains are turned in the modified plan, which is significantly lower than the average of 101.4 trains which are turned in the original timetable in order to maintain the schedule. This implies that almost the same regularity can be obtained with the modified timetable by turning approximately 20 times less trains than needed to obtain the same regularity in the original plan.

The average regularity is improved by 2.9 percentage points, which is a significant improvement obtained by using only 4 extra trains. Furthermore less recovery is needed to obtain a significantly better result. The results show that even smaller improvements in the buffer times have a significant impact on the overall regularity and average delay. Finally the experiment shows that not only is the regularity improved but the timetable becomes more robust, since less recovery is needed.

A third experiment with the timetable with 12 lines has been constructed. The buffer times are improved by running the original timetable with no lines merging. This results in better buffer times for all A lines in Hillerød, for all B lines in Høje Taastrup and for all C lines in both Klampenborg and Frederikssund. The results from the experiments are shown in Table 24. As it was expected the results with more buffer time are considerably better than the results from the experiment with the original timetable where lines are merging. The average regularity is improved with 11.5 percentage points. This is a notable improvement and can be explained by the low regularity for the original timetable with 12 lines. It should be noted though that 100 trains are necessary to run this improved plan whereas the original plan could be run with 93 trains, so the cost is also considerably higher.

Recovery	**Average Delay**		**Regularity**		**Reliability**		**Trains affected**	
	Original plan	Modified plan	Original plan	Modified plan	Original plan	Modified plan	Original plan	Modified plan
None	3.45	1.53	50.82	77.11	100	100	-	
Take out (a)	1.35	1.05	83.40	88.25	76.86	81.12	5 lines	5 lines
Take out (b)	0.94	0.87	91.06	92.38	56.16	65.10	6 lines	6 lines
Turn around (1)	1.53	1.12	79.37	88.76	74.49	88.50	286	146.8
Turn around (2)	2.10	1.47	65.68	78.43	87.80	98.00	120.6	21
Turn around (3)	1.44	1.11	80.34	88.07	72.44	90.38	300.2	111.2
Replace (1)	1.92	1.42	69.61	81.12	100	100	153	71.8
Replace (2)	2.50	1.52	56.57	77.59	100	100	66.6	7.8
Replace (3)	1.94	1.47	69.85	78.76	100	100	173.2	36.4

Table 24: Experiments with improved buffer times for the proposed timetable with 12 lines

Another experiment with the timetable with 12 lines is conducted where all lines are merged in a different way to give all lines at least 6 minutes buffer times at all end stations. The reason for this is that in the previous experiment even though not merging any lines resulted in better buffer times for some lines, the A lines still had only one minute buffer time in Køge and the B lines had only 1 minute buffer time in Farum. The experiment is made to examine the effect of larger and more homogeneous buffer times. This experiment resulted in an improvement of the average regularity of 16.4 percentage points compared to the original timetable with 12 lines and 4.8 compared to the above experiment with 12 lines where no merging was done to improve the buffer times. In this experiment 99 trains were necessary to run the plan.

This result implies that larger buffer times need to be allocated to all lines to give the best result. It does not necessarily result in a more robust plan if some lines obtain larger buffer times while other lines have very small buffer times, since any disturbances on the lines with small buffers might influence on all lines.

22.2.1 Experiments with a limited amount of buffer time at end stations

Knowing that large buffers in the shunting times result in more robust timetables it is interesting to examine whether there is a limit to when more buffer time increases the robustness, i.e. if the regularity stabilizes at a point even though more buffer time is added. This experiment is run on timetables with 9 lines (actual 2006), 10 lines (proposed timetable with improved buffer times) and 11 lines, with no recovery used and with 50% probability of delays occurring.

By changing the minimum shunting times 10 experiments are made where all lines can gain $1, 2, \ldots, 9, 10$ minutes at the end stations. First the experiment with the timetable with 9 lines is examined. In Figure 66 the regularity for each of the 9 lines after a simulation running for 750 minutes is given as a function of the buffer time $(0, 1, 2, \ldots, 9, 10$ minutes). The coloured curves in the figure represent the 9 different lines and the bold black curve is the overall regularity.

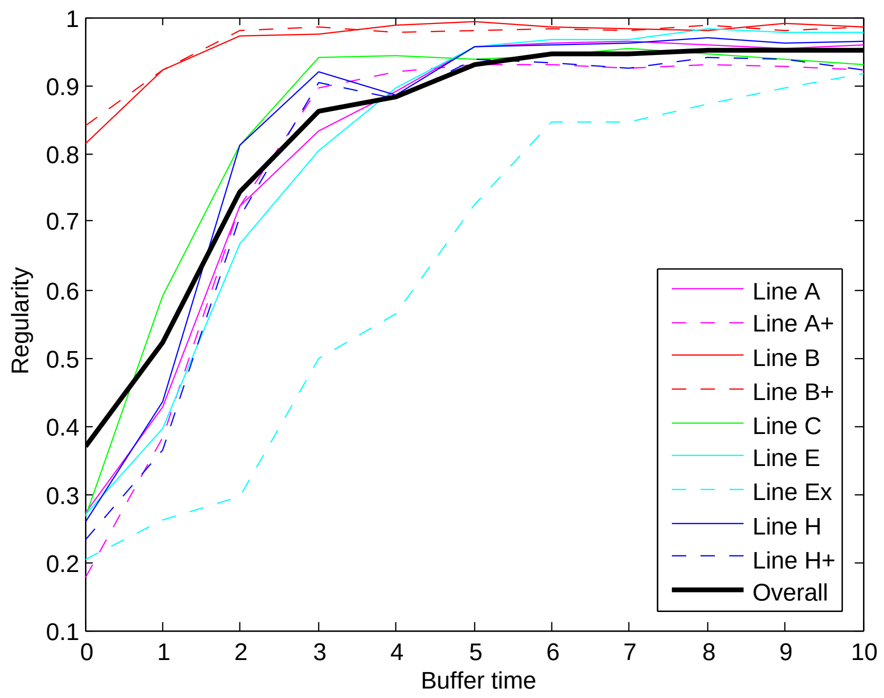


Figure 66: Timetable with 9 lines

The figure shows that the regularity increases heavily when the buffer time is increased from 0 to 3 minutes. This confirms that the buffer times at end stations have a significant positive effect on the regularity. At the point where buffer time reaches 5 minutes the regularity for most of the lines stabilizes, which in this case means that increasing the buffer time further than 5 minutes does not affect the regularity much. The regularity for line Ex does not stabilize, more buffer time will increase the regularity on this line further. The experiment is expanded to higher buffer times and the regularity of this line also stabilizes.

The experiments with timetables with 10 and 11 lines give similar results, see Figures 67 and 68. In the experiment with the timetable with 10 lines the regularity also stabilize when the buffer time reaches 5 minutes, similar to the timetable with 9 lines, except that all the 10 lines reach stabilization and many of the lines are already stabilized when buffer time reaches 3 minutes. In the experiment with the timetable with 11 lines the regularity does not stabilize before the buffer time reaches 8 minutes. Again a single line (line F) does not reach stabilization within the given buffer times.

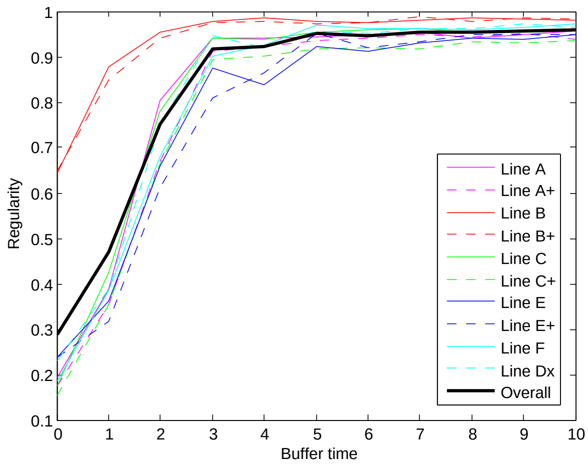


Figure 67: Timetable with 10 lines

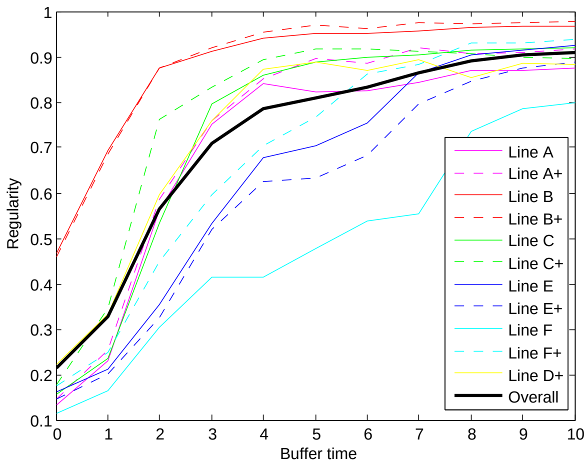


Figure 68: Timetable with 11 lines

Depending on the timetable and the line structure the limit for when more buffer time does not improve the regularity any further will vary. This experiment shows that buffer time at end stations has a positive effect on the regularity, but at some point the regularity will stabilize and more buffer time will not improve the regularity further. Furthermore the experiment shows that for these timetables the possibility of gaining minimum 3 to 5 minutes a the end station has a very positive effect on regularity but more buffer times are not necessarily important, i.e. a few minutes of buffer time are enough but very important.

22.3 Homogeneous stopping pattern

In the article *Reliability and heterogeneity of railway services* [23] it is concluded that the more homogeneous the timetable is according to stopping pattern, cycle time and line structure, the more robust the plan will be.

Many of the timetables developed by DSB S-tog and used in this project use a combination of fast and slow lines. Some lines cover all stations on train series and some lines skip smaller stations. There are also big differences between cycle times for the different lines in the timetables. Some lines have a cycle time of 200 and some only 120 minutes. This makes the timetables heterogeneous.

The proposed timetable with 10 lines is more homogeneous than the actual timetable from 2003 also with 10 lines. It is more homogeneous according to cycle times and stopping patterns because all lines in pairs stop at the same stations e.g. A and A^+. When modified to be somewhat similar according to buffer times at the end stations the more homogeneous timetable results in a higher regularity hence a higher robustness.

The proposed timetable with 12 lines is considered to be very homogeneous concerning line structure and stopping patterns. Only 3 different types of lines are used to cover the entire network. If other similar timetables with 12 lines where accessible, the proposed timetable might have been proven to be more robust than a less homogeneous timetable with 12 lines.

Because of the data available for this project, it has not been possible to fully confirm the hypotheses about robustness and homogeneity. The timetables have to be compared on a very similar basis, which is not possible, because a limited number of different timetables were accessible within the time frame of this project.

22.4 Even distribution of tracks on København station

The hypothesis concerning even distribution of tracks on København station is explored. It is investigated whether it can have a positive effect on regularity if trains are equally distributed between the two tracks at København. Even headways should result in better buffer times between the trains for all lines, and therefore it should improve the robustness of the plan. Note that there are two tracks in each direction at København station.

In the proposed plan with 12 lines, the tracks are originally allocated such that all C line trains (C, C^+, Cx and Cxx) use the first track at København. All A line trains and all B line trains use the second track. In this experiment every other line (given from their departure times at København) use either the first or the second track at København respectively. A similar experiment is conducted for the actual timetable from 2003.

The results did not show any improvements in neither regularity nor average delay. The reason is probably that this minor improvement is too small to affect the results. In a scenario where tracks were evenly distributed at all stations with double tracks an improvement might have been seen. Therefore the hypothesis stating that even distribution of tracks will results in better regularity cannot be accepted on the base of the results.

22.5 Numbers in queues

In the following the numbers of trains in queues for stations and queues for routes are explored. In Table 25 the numbers in queues for the stations are observed for all the main timetables, run with delays but without recovery. It is assumed that the numbers will be similarly distributed for the different timetables if recovery was used (naturally the average number in queue would be smaller). In Table 26 the numbers of trains in queue for the routes to the stations are shown. In the tables the maximum number in queue for the 5 replications are observed. Only stations and routes where a maximum number of 2 or more trains in queue appeared are included. It can be seen that most of the stations and routes where queues occur, are in the central section, which was also the expected result, because all the trains are travelling through this section of the network. Furthermore Enghave station appears to have a maximum of 2 trains in queue for a large number of the timetables. This is probably because several lines meet in Valby before going to Enghave and then to Dybbølsbro, and both Valby in the northern direction and Dybbølsbro have double tracks, and therefore Enghave, which has a single track only, defines a bottleneck. This results in queues.

Note that there are no trains in queues for the stations when simulating the timetable for 2006. Note also that the results for the circular timetable have been omitted, due to the different structure.

It should be noted from comparing the two tables that the number of queues for the routes is somewhat larger than the number of queues for the stations. This is due to the way safe headways are handled in the model. Trains are held back on the routes to maintain safe headways in the model. Queue on a station occurs when the station is occupied by another train. This situation only arises when a trains is delayed more than 90 seconds at the station, because otherwise the next train will be held back at the route to the station. For example if a train is delayed 30 seconds at Enghave this does not influence the next train because it arrives at least 90 seconds later due to the safe headways on the routes. Naturally these numbers does not apply for the larger stations where the dwell time alone is 30-60 seconds and therefore a smaller amount of delay will cause a queue on the station. This might also be the reason for the largest queues arising in the central section, because this is where the dwell times are largest (30 seconds on most stations) and also the largest amounts of delays occur, because of the large number of passengers etc. Therefore the risks of queues at the stations in the central section are larger, not only because all trains are travelling through these section.

Number	**Station**	**2006**	**2003**	**10 lines**	**11 lines**	**12 lines**	**Combination**
12	Dybbølsbro N	0	0	0	0	0	1
161	Dybbølsbro N	0	0	0	0	1	1
92	Dybbølsbro S	0	1	1	1	0	1
16	Enghave N	0	2	2	2	2	1
96	Enghave S	0	1	1	1	1	1
44	København N	0	1	2	1	1	2
45	København N	0	1	2	2	3	2
124	København S	0	1	1	1	1	1
125	København S	0	1	1	1	2	2
51	Nordhavn N	0	0	0	0	1	1
132	Nordhavn S	0	1	1	2	2	1
52	Nørreport N	0	1	1	1	1	1
133	Nørreport S	0	2	2	2	2	2
64	Svanemøllen N	0	0	1	1	1	1
65	Svanemøllen N	0	0	2	0	0	1
145	Svanemøllen S	0	1	1	1	1	1
146	Svanemøllen S	0	0	2	1	0	1
74	Vesterport N	0	2	1	1	2	1
154	Vesterport S	0	0	0	0	1	1
79	Østerport N	0	1	1	1	1	1
159	Østerport S	0	1	1	1	1	1

Table 25: Queues on stations

Number	Station	2006	2003	10 lines	11 lines	12 lines	Combination
83	Avedøre S		2				
5	Ballerup N					2	
161	Dybbølsbro N						2
92	Dybbølsbro S	2	2	2	2	2	2
14	Ellebjerg N				2		2
16	Enghave N	1	2	2	3	3	2
96	Enghave S	1	2	2	2	1	1
106	Hellerup S	1	2	2	2	1	1
36	Ishøj S			2			
44	København N	1	1	1	1	1	2
45	København N	1	1	1	1	2	1
124	København S	1	1	1	1	1	1
125	København S	2	1	1	1	1	1
130	Malmparken S				2		
51	Nordhavn N					2	
132	Nordhavn S	2	2	2	2	4	2
52	Nørreport N	1	2	1	1	2	1
133	Nørreport S	2	3	3	2	2	3
64	Svanemøllen N	1	1	2	1	2	2
145	Svanemøllen S	1	1	1	2	2	1
66	Sydhavn N			2			2
147	Sydhavn S			2			
149	Valby S		2				2
150	Vallensbæk S		2				
74	Vesterport N	2	3	3	3	3	2
154	Vesterport S	1	1	1	1	1	1
79	Østerport N	2	2	2	2	2	2
159	Østerport S	1	2	2	2	2	2

Table 26: Queues on routes

23 Comparison of timetables

In the following sections results from experiments with all the different timetables presented earlier in this chapter will be compared. Both results from experiments with the original timetables and the modified versions will be compared, mainly to examine the effect more lines, different line structures and more buffer times have on regularity and robustness. The results from experiments without and with recovery are explored. Only recovery methods with some of the thresholds used are explored, since the other experiments with recovery methods show similar results.

Generally it is seen that the fewer lines the better the regularity and robustness, but it is also shown that this is not the only important factor. Furthermore it is confirmed that the circle and the combination timetable are robust.

23.1 Comparison with delays and without recovery

In Table 27 the results are shown for the experiments without recovery for each of the timetables. Note that the reliability is 100% for all experiments since no departures are cancelled. Note also that the regularity for the circular line plan does not include the regularity on the central line. The ranking in the table is made according to regularity.

Timetable	**Average Delay**	**Regularity**	**Ranking**
2006 (9 lines) - line Ex taken out at København	0.64	96.10	2
2006 (9 lines)	0.77	93.96	5
2003 (10 lines) - line Ex taken out at København	0.81	93.30	7
2003 (10 lines)	0.85	92.80	8
10 lines	1.37	85.49	12
10 lines - line Dx terminating in Buddinge	1.22	87.54	9
10 lines - line Dx terminating in Buddinge and improved buffer times	0.78	94.28	4
11 lines	1.22	86.80	10
12 lines	3.45	50.82	14
12 lines and no lines merging	1.53	77.11	13
12 lines and improved buffer times	1.19	85.93	11
Circular	0.61	96.32	1
Combination	0.80	93.35	6
Combination with improved buffer times	0.71	95.31	3

Table 27: Experiment with delays

The circular timetable gives the highest regularity, but not much better than the timetable with 9 lines

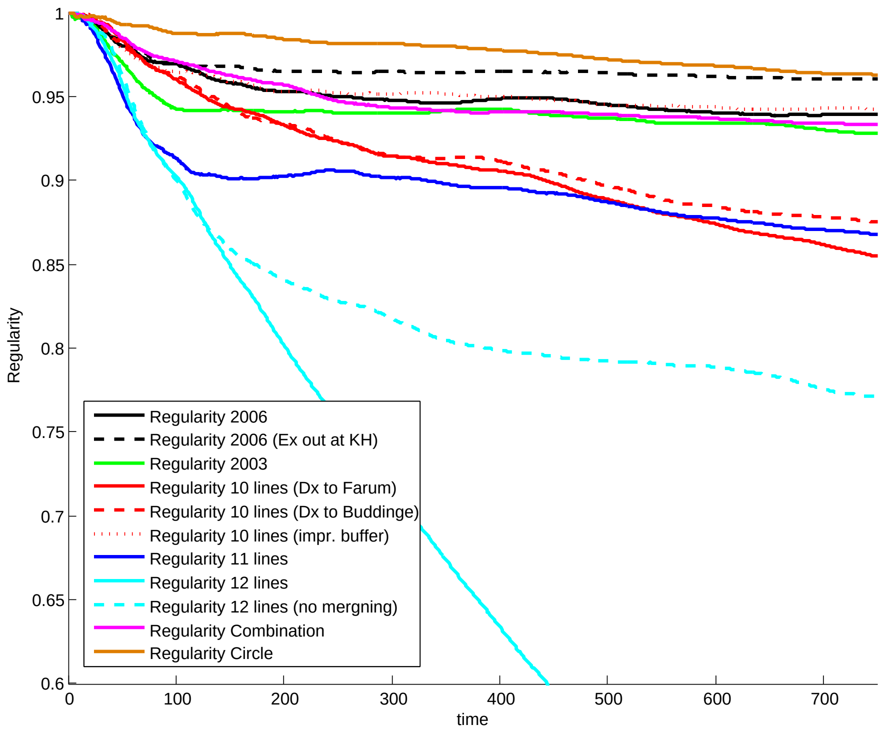


Figure 69: The regularity for the different timetables with no recovery

for 2006. The combination timetable also gives reasonable regularity, on the level of other timetables with 10 lines in the central area.

The experiments with the proposed plan with 10 lines with line Dx terminating in Buddinge and improved buffer times at end stations actually becomes fourth best, as opposed to third worst before the adjustments. In Figure 69 the improved plan with 10 lines is displayed together with the other results from the experiments with the different timetables with delays but without recovery.

Not surprisingly, as seen in Figure 69, the overall results is that the regularity decrease as the number of lines increase, since more lines and departures result in smaller headways. To confirm this conclusion a small experiment is conducted. In the timetables with 11 and 12 lines the lines are removed one by one to see how fewer lines affect the regularity. The structure of the timetable with 12 lines does not change much when lines are removed, because it is very homogeneous. This is not the case for the timetable with 11 lines, but this addition is made to broaden the basis of the experiment. The result is presented in Figure 70, where the regularity for the timetables with respectively 11 and 12 lines are changed to fictive timetables with 4, 5, 6, . . ., 9, 10 and 11 lines. As expected the results show that more lines cause a lower regularity. The interesting result is that this relationship is non-linearly decreasing.

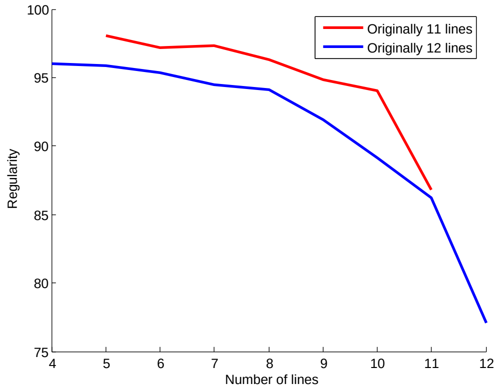


Figure 70: Regularity when the number of lines increase

23.2 Comparison with recovery methods

23.2.1 Turn around before the end station

The timetables are compared when trains are turned if more late than they can gain while shunting. The results are shown in Table 28. Note again that the number of trains turned is an average for the 5 replications and therefore it is non-integral. The regularities for the lines are also displayed in Figure 71.

Timetable	**Average Delay**	**Regularity**	**Reliability**	**Trains turned**	**Ranking**
2006 (9 lines) - line Ex taken out at København	0.58	96.64	97.17	22.4	1
2006 (9 lines)	0.71	95.07	99.45	4.6	5
2003 (10 lines)- line Ex taken out at København	0.69	94.80	94.92	60	6
2003 (10 lines)	0.75	93.04	94.15	63.0	7
10 lines	0.69	95.29	84.23	111	4
10 lines - line Dx terminating in Buddinge	0.67	95.82	85.70	101.4	2
10 lines - improved buffer times	0.69	95.48	99.49	5.4	3
11 lines	0.96	91.44	97.50	30	8
12 lines	1.44	80.34	72.44	300.20	10
12 lines - no lines merging	1.11	88.07	90.38	111.2	9

Table 28: Experiment with Turn around when more delayed than buffer time at end stations

As for the experiments without recovery, the results in these experiments show that the regularity

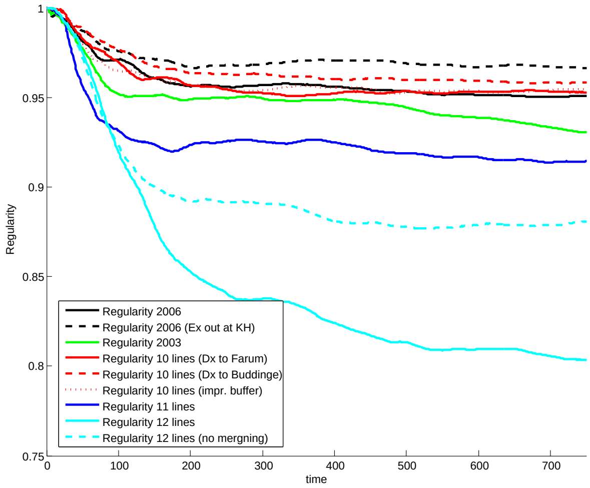


Figure 71: The regularity for the different timetables with turn around when more delayed than buffer at terminals

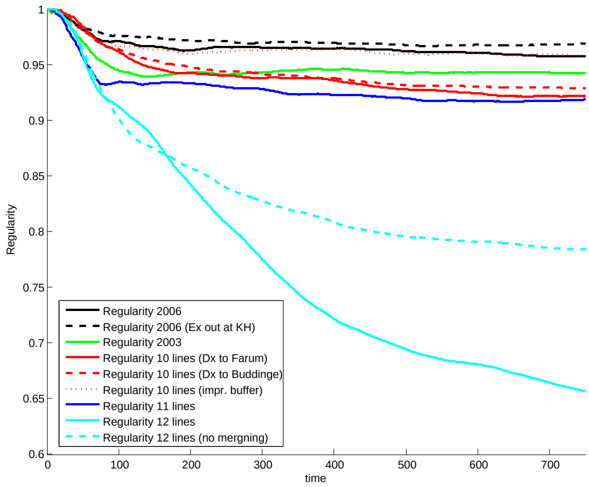


Figure 72: The regularity for the different timetables with turn around when 5 minutes delayed

decrease as the number of lines increase, except for the results for the improved timetable with 10 lines which is better than the timetable for 2006 when line Ex is not terminated at København. Note the results for the proposed timetable with 10 lines (Ranking 2, 3 and 4). The regularities are similar but the number of trains turned and thereby the reliabilities are very different. The plan with improved buffer times gives a very high reliability. This confirms the conclusions about more buffer time resulting in a more robust timetable.

The regularities for the experiments where trains are turned if more than 5 minutes late are shown in Figure 72. Note the difference of the ranking of the lines in the two figures where trains are turned. The ranking is different because the thresholds for turning are different. In Figure 72 it is seen that the regularity of the timetable with 11 lines is almost as good as one of the timetables with 10 lines and on the other figure it is a lot worse. Note also that when the threshold is the buffer time, the improved timetable with 10 lines ends up with a better regularity than the timetable with 9 lines, but at the cost of turning more trains.

The threshold of 5 minutes is equal for all the timetables whereas the threshold, where trains are turned if more late than what they can gain at the end stations depends on the size of the buffer times in the specific plan, and therefore differs for the timetables. This implies the importance of comparing on the same basis, since it is difficult to compare the results when the buffer times vary in size, and thereby a significantly different number of trains are turned to maintain the schedule.

23.2.2 Cancellation of lines

Experiments with Take out are made with a threshold of 90%. The results are seen in Table 29 and Figure 73. Note that the timetable for 2006 where line Ex is taken out at København and the proposed timetable with 10 lines and improved buffer times are missing in the graph since no lines were cancelled in these experiments.

Timetable	Average Delay	Regularity	Reliability	Lines cancelled	Ranking
2006 (9 lines) - line Ex taken out at København	0.64	96.10	100	0	2
2006 (9 lines)	0.70	95.09	88.96	3	6
2003 (10 lines)- line Ex taken out at København	0.70	94.61	88.80	3	9
2003 (10 lines)	0.70	94.93	89.69	4	8
10 lines	0.84	93.06	79.21	3	11
10 lines - line Dx terminating in Buddinge	0.81	93.31	82.01	3	10
10 lines - improved buffer times	0.69	95.25	88.78	3	4
11 lines	0.70	95.19	67.75	4	5
12 lines	0.94	91.06	56.16	6	13
12 lines - no lines merging	0.87	92.38	65.10	6	12
Circle	0.58	96.62	99.54	1	1
Combination	0.67	95.07	86.39	3	7
Combination - improved buffer times	00.65	95.88	96.33	2	3

Table 29: Experiments with cancellation of lines at 0.9

The results show that the circular timetable turns out to be the best plan, the timetable for 2006 turns out to be next best and the plan with 12 lines turns out the be worst as expected. The proposed timetable with 10 lines is not particularly good but also has low buffer times at the end stations which results in delays propagating and regularity decreasing. The improved timetable with 10 lines is very good and has a high regularity. The combination line was expected to be good but turns out to be on the same level as most of the other timetables with 10 lines in the central area. The combination timetable with improved buffer times gives much better results.

The timetable with 11 lines gives very high regularity in this experiment. It is better than some of the timetables with 9 and 10 lines. As the figure shows the regularity of timetable with 11 lines is decreasing for the first 100 minutes and then it begins to increase and ends up among most of the other lines with a regularity around 95%. This emphazises the impact of recovery.

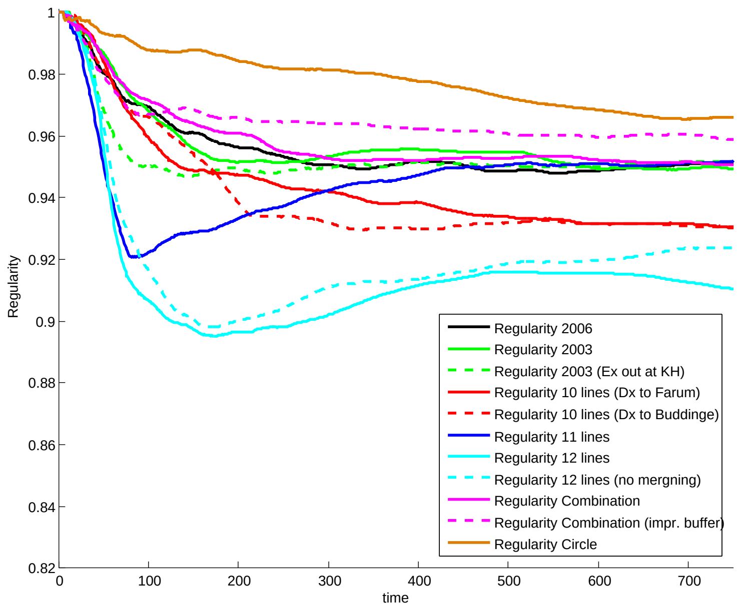


Figure 73: The regularity for the different timetables with cancellation of lines at 0.9

The timetable with 12 lines is not as bad as in the other experiments. It should be noted that 6 lines are ending up being cancelled in some of the replications, which means that only 6 lines are actually running for some of the time during the simulation.

23.2.3 Replace train at København

In the last experiment trains are replaced if they are more late than they can gain while shunting. The results are shown in Table 30 and Figure 74. Note that the reliability is 100% because no departures are cancelled when using Replace. The ranking of the combination timetable is an improvement compared to the earlier results. In experiments with thresholds of 2.5 and 5 for trains being replaced the combination timetable also obtains a very high ranking without replacing a high amount of trains. The recovery method Replace results in high regularity for the combination timetable. This result confirms that the three recovery methods have very different effect on the different timetables.

Timetable	Average Delay	Regularity	Reliability	Trains replaced	Ranking
2006 (9 lines) - line Ex taken out at København	0.63	96.15	100	12.8	1
2006 (9 lines)	0.75	94.35	100	11.4	6
2003 (10 lines) - line Ex taken out at København	0.75	94.65	100	23.6	5
2003 (10 lines)	0.82	93.33	100	32.20	7
10 lines	0.89	92.19	100	59.4	9
10 lines - line Dx terminating in Buddinge	0.88	92.22	100	56	8
10 lines - improved buffer times	0.74	94.85	100	0.6	3
11 lines	1.08	89.32	100	23	10
12 lines	1.94	69.85	100	173.2	12
12 lines - no lines merging	1.47	78.76	100	36.4	11
Combination	0.71	94.72	100	9	4
Combination - improved buffer times	0.68	95.53	100	0.6	2

Table 30: Experiment with Replace when more delayed than buffer time at terminals

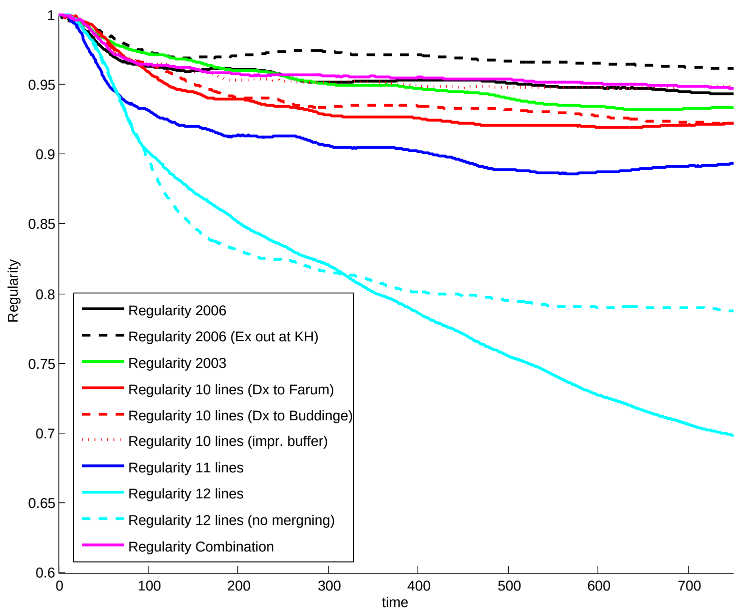


Figure 74: The regularity for the different timetables with Replace when more delayed than slack time at end stations

24 Conclusion on the experiments

The conclusion on the experiments with the three recovery methods is that when the overall regularity is high, turning trains gives the best overall results with regards to both regularity, average delay and reliability. Cancelling lines is only activated when the regularity is low and therefore this recovery method is appropriate for medium and larger disturbances. The recovery method of cancelling lines generally has the worst reliability. Replacing trains is not as effective as turning trains, because the trains can be replaced at København station only. On the other hand this recovery method has a very high reliability, since no departures are cancelled, which means that only the passengers in the train that is scheduled to be replaced are affected.

The experiments with delay showed that more delay results in lower regularity, and the relation is non-linearly decreasing. Another conclusion is that large delays naturally have a more significant effect on regularity than smaller delays, but also that secondary delays have a significant impact on regularity, so smaller delays should also be eliminated if possible.

One of the main conclusions from the experiments is that the amount of buffer time at the end stations has a considerable effect on the robustness. A minimum of three to five minutes (in these experiments) of buffer at the end stations results in high regularity and few trains affected when the recovery methods are used. This indicates that a timetable becomes more robust when a reasonable amount of buffer time is used. Furthermore it is shown that the necessary amount of buffer time is limited, which makes it realistic to implement the result. It should be noted though, that if more buffer time is added more trains are needed, which is a negative result seen from an economical point of view. Since the amount of necessary buffer time is limited it should be possible to construct timetables with reasonable buffer times to achieve a higher robustness.

Investigating the occurrences and sizes of queues showed that most of the stations and routes where queues occur, are in the central section, which was also the expected result, because all the trains are travelling through this section of the network. Furthermore it was concluded that an additional reason for the queues arising in the central section was because of the larger dwell times and higher amounts of delays.

The conclusion for the comparison of the different timetables is that not surprisingly the number of lines in a timetable seems to have a significant impact on the regularity and thereby robustness of the plan. In general a higher number of lines, with the same frequency of 20 minutes on all lines, results in a lower regularity. Overall the improved timetable with 10 lines turns out to give the best results with regards to number of lines, regularity and number of affected trains. The timetable for 2006 is also very good, but the consequence of this plan is a lower customer service level since it includes one line less. Furthermore it is concluded that the number of lines is not the only important factor when considering robustness of a timetable. A timetable with 10 lines is shown to have a higher regularity than a timetable with 9 lines because of better buffer times at the end stations.

A larger number of lines and the same frequencies results in a larger number of departures, which improves the customer service level. Therefore it would be desirable if it was possible to use a timetable with more than 10 lines, to raise the customer service level. The conclusion from the experiments with the timetable with 12 lines is that the achieved regularities are not acceptable. A regularity of 88.76% is obtained with the timetable with 12 lines and no lines merging when trains are turned. The highest regularity of 92.38% is achieved when lines are cancelled. This is a reasonable regularity, but the result should not be accounted for in recommending running 12 lines since the higher regularity was achieved by cancelling 5-6 lines. The timetable with 11 lines might be possible though since some of the experiments resulted in a regularity at the same level as for the timetables with 10 lines.

The constructed circular timetable resulted in high regularity as expected. It is better than all the other timetables in all the experiments. It should be noted though, that the timetable with 9 lines is almost as good. The regularity is only approximately 0.4 percentage points lower for the timetable for 2006. The combination timetable can be compared with the other timetables with 10 lines through the central area. It is better that these timetables in all the experiments where the combination timetable has improved buffer times. This is not surprising, because the lines are shorter in the combination timetable. Note that the circular and combination timetables are not necessarily directly compatible with the current structure of S-train network. These two timetables are meant as prototypes and have the purpose of testing an entirely new line structure.

25 Further research

In this chapter it is discussed how the model can be expanded to broaden the use of it or to increase the level of detail. Furthermore some additional experiments are mentioned.

25.1 Further development of the model

To make the recovery strategies more realistic additional recovery methods could be implemented, but most importantly the recovery methods should be combined in a way in accordance with how recovery is done in the real system. A decision tool for which recovery method to use in particular situations should be developed to make the recovery methods more realistic. This involves analyzing in detail, when different recovery methods are applied by the controllers.

The delay added in the model is made from historical data, which makes it very trustworthy. In the historical data both late and early trains are observed. Since an assumption about trains never leaving earlier than scheduled is made, the delay distributions are not directly applicable in the model. In the model compensation is made by only adding delay every second time a train enters a station (delay is added with 50% probability). To make the results more accurate two things can be done. Either the assumption should be adjusted and letting trains depart earlier at stations. This way the delay distribution would be strictly correct. Another way to make the model more accurate could be to determine a more precise delay probability instead of 50%.

Furthermore some other assumptions made in the model could be adjusted to increase the degree of detail in the model. Generally the assumptions concerning only examining a worst case scenario could be omitted to broaden the use of the model. This means that data should be modified to simulate a day in details and not only rush hour situations, with regards to number of trains used, lines inserted and cancelled etc. Concerns about marshalling and train specific data could also be added to broaden the use of the model.

Overtaking could be made possible. In Arena this can be done by using a Resource module for the platforms instead of a Hold and a Delay module. At a station where overtaking is possible there are two tracks. A Resource with capacity 2, could be used to represent the two tracks. This would imply the need for a ranking rule, to specify the order of the entities in the queue to the resource (the station). This way a train with a higher rank could enter the station earlier than one with a lower rank, if they are both waiting to enter the station. Furthermore it might be possible to gain time at a few routes in case of delays. This could also be implemented in the model if possible.

To increase the level of detail in the model the correct headways in the entire network could be added. This is very simple to implement, but the information have not been available for this project.

In the real system there is only one track between Farum and Værløse because of an old bridge (Fiskebækbro). The trains use the same track in both directions. This is omitted in the model, but could be implemented by adding a fictive station between Farum and Værløse which trains in both directions should visit.

Finally it would be an improvement in the model if additional measures of the number of primary and secondary delays were included, to make it easier to display where the problems occur in the network. This is a difficult task, and requires very specific definitions on how primary delays are measured.

25.2 Further experiments

- The comparison of the timetables could be expanded with more timetables to generalize the results. Furthermore timetables which were identical except for one feature could be of use to determine more thoroughly whether a specific hypothesis could be accepted.

- Experiments where the trains may switch to another platform if the scheduled platform is occupied should minimize secondary delays. The result is investigated in [4] and could be demonstrated using the model developed in this project. In Arena switching between platforms can be implemented by using resources for the platforms.

- Experiments with double tracks at all the stations in the central area (Dybbølsbro to Svanemøllen), could be used to examine the effect of minimizing the bottleneck in this section of the network.

- Experimenting with equally distributed planned headways in the timetables should result in secondary delays being minimized. This result is stated in [3] and could be examined with the model developed in this project, by comparing timetables with and without this feature, if such timetables were available or developed.

- Further experiments with distribution and propagation of delays might be interesting, to examine the effect of primary and secondary delays thoroughly.

- Experimenting with quantifying customer service level (other than by number of departures as in this project e.g. average door-to-door travel time) to weight robustness up against service level, since a higher service is desirable but not at the expense of the robustness of the plan.

26 Conclusion

The objective of this project was to gain knowledge about the construction of robust timetables for DSB S-tog. The objective has been achieved by experimenting with timetables with different features. Several important factors regarding robustness were investigated. Robustness of timetables was measured by systematically simulating multiple timetables affected by disturbances. The approach of simulation of timetables was new in connection with DSB S-tog.

In order to obtain knowledge about railways, simulation, robustness and recovery several articles from the literature have been studied. An objective in the first phase of the project was also to gain knowledge about the company DSB S-tog. This phase of the project served as a good basis for the understanding of the problem and development of the model.

Another purpose of the project was to study the simulation program Arena. A generic model of the S-train network has been modelled and build in Arena. The process of building and implementing the model turned out to be the longest phase in the project. One of the reasons was that a precise model would make the results of the later simulation much more useful. The model build in this project can simulate all arrivals and departures of trains in the entire network during a day within seconds.

Three different recovery methods have also been implemented in order to broaden the basis for the experiments. Furthermore an additional objective in the project was to compare different recovery methods, representing different recovery strategies used by DSB S-tog. Turning trains proved to be the best recovery method when the regularity is high, whereas the more drastic approach of cancelling lines turned out to be the best recovery method when the overall regularity is low.

The aim of this project was to get an impression of what effect different features in timetables have on the robustness of the plan. In order to examine the effect a large number of similar timetables were necessary. Since DSB S-tog have made only minor changes in the timetables over the past 5 years, only a few very different timetables are completely developed and directly available for this project. Therefore parts of the project turned out to include developing new timetables. Fourteen different timetables have been implemented to test the different hypotheses regarding robustness. Five of these timetables were developed by DSB S-tog, seven were further modifications of the existing timetables and two timetables were developed specific for this project.

The results from the experiments with the different timetables showed that the number of lines in the plan has a large impact on the overall regularity. Furthermore the results illustrated that there are other factors which also influence the robustness of the timetable. The amount of buffer times at the terminal stations turned out to have a significant effect on the robustness. Results also showed that it is important how the total amount of buffer time is allocated to the different lines in the plan, and that the necessary amount of buffer time to create a robust timetable is limited. Finally testing totally different line structures also proved to have a positive effect on the robustness of the plan, and the timetable developed with a circular line in the central section actually resulted in the best robustness in all the experiments.

A Evaluation of simulation using Arena

In this appendix the Arena simulation software is evaluated. Since we have not had any experience with other simulation tools this evaluation will be a subjective examination of the pros and cons by using Arena. Some of the detail in the advantages and disadvantages are very specific and requires some knowledge about Arena. Generally we have found Arena easy to use and very suitable for this project.

Advantages:

- Generally Arena is extremely versatile. It can model anything from a production line to a hospital waiting room. Furthermore both discrete and continuous simulation is possible.
- Arena is easy to use for beginners, because of the drag and drop feature. It requires no knowledge about programming, but knowing the general syntaxes makes the modelling easier. When building a model in Arena many different modules are connected. Using the modules is easy because all values are shortly explained by their names and in many cases the default value can be used. Mistakes about unassigned values are rare because of the specifications in the modules. A feature offers help when building an expression where Arena defined variables or attributes are used. This feature also minimizes errors.
- Compared to programming the simulation model oneself in e.g. Java, it is very time saving to use Arena because of the many defaulted features.
- Arena has great graphics, to support the animation or to make the model easy to read and demonstrate.
- Arena provides good test conditions. There is the possibility of stepping through the modules in the model while simulating, where the modules can be highlighted when an entity is travelling through. The modification of variables and attributes can be watched while stepping through the simulation. Finally the simulation can be run with a trace which makes it possible to follow every move of the each specific entity during the simulation. The movement can be seen in the output file (.out).
- The structure of the model is shown in the Navigate project bar. This gives a well-arranged view of the model. Also the possibility of making 'named views' of specific parts of the model, makes the model more structured.
- Arena is compatible with most Microsoft products e.g. Excel and Access. This makes it possible to read and write data from e.g. Excel instead of writing it manually in the Arena model. This feature is limited to only reading and writing numbers and a limited number of characters, which is a weakness.
- In Arena a large amount of 'SMART models' are included. These models demonstrate different specific features and are of good use for learning about the logic of the modules.

- The possibility of running more replications makes it easy to compensate for e.g. stochastic data and variance.
- The computational time is reasonably fast. The model made in this project can simulate 5 replications of all arrivals and departures of trains during a day within seconds.

Disadvantages:

- The help function in Arena is sometimes difficult to use, it is not always explicative enough and is short of examples. With basic problems about how different modules or tools are used the help feature is good. It is not possible to ask specific questions and therefore the more complex problems are hard to solve using the help feature.
- A disadvantage in Arena is that the variables cannot be organized or sorted alphabetically in the Variable Data module. This makes the view of the variables very chaotic.
- The Decide module in Arena could be improved with a copy feature. This would make it more simple to generate several similar if-cases.
- In Arena it is possible to define a set of entities, station names, queues etc., but it is not possible to determine if a specific object e.g. an entity is a member of a set. This improvement could shorten and simplify the 'N-way by condition' Decide modules. As an example it has to be decided if the current station (*AttStation*) equals one of 20 stations. The easiest solution would be to create a set containing the 20 stations and then examining whether the current station is a member of that set. This is not possible in Arena, the solution here is to examine whether the current station equals the first, the second station, . . . or the 20'th station.
- Arena is not practical for microscopic simulation because the model will need to consist of a huge number of modules. In such cases specific simulation tools for e.g. railways or road networks might be more suitable.

B Output file

```
SIMAN System Trace Beginning at Time: 0.0

Seq# Label            Block    System Status Change
----- ---------------- -------- ---------------------------------------------

Time:  0  Entity: 2
    1 6$               CREATE
                                 Entity Type set to Train 1
                                 Arrival stream terminated
                                 Batch of 1 Train 1 entities created
    2 7$               ASSIGN
                                 Create 10.NumberOut set to 1.0
    3 0$               STATION
                                 Entity 2 entered station Station Hillerod
    4 12$              DELAY
                                 Delayed by 0.0 until time 0.0
    5 4$               ASSIGN
                                 Hillerod.NumberIn set to 1.0
                                 Hillerod.WIP set to 1.0
    6 42$              STACK
                                 Saving 1 copies of internal attributes
    7 16$              QUEUE
                                 Entity 2 sent to next block
    8 15$              SEIZE
                                 Tally Hillerod.Queue.WaitingTime recorded 0.0
                                 Seized 1.0 unit(s) of resource Platform Hillerod
    9 14$              DELAY
                                 Delayed by 2.0 until time 2.0
Time:  0  Entity: 3
   19 64$              CREATE
                                 Entity Type set to Train 2
                                 Arrival stream terminated
                                 Batch of 1 Train 2 entities created
   20 65$              ASSIGN
                                 Create 11.NumberOut set to 1.0
   21 2$               STATION
                                 Entity 3 entered station Station Hundige
   22 70$              DELAY
```

```
                                   Delayed by 0.0 until time 0.0
   23 5$               ASSIGN
                                   Hundige.NumberIn set to 1.0
                                   Hundige.WIP set to 1.0
   24 100$             STACK
                                   Saving 1 copies of internal attributes
   25 74$              QUEUE
                                   Entity 3 sent to next block
   26 73$              SEIZE
                                   Tally Hundige.Queue.WaitingTime recorded 0.0
                                   Seized 1.0 unit(s) of resource Platform Hundige
   27 72$              DELAY
                                   Delayed by 2.0 until time 2.0
Time:  2  Entity: 2
   10 57$              ASSIGN
                                   Hillerod.WaitTime set to 0.0
   11 21$              TALLY
                                   Tally Hillerod.WaitTimePerEntity recorded 0.0
   12 23$              TALLY
                                   Tally Hillerod.TotalTimePerEntity recorded 2.0
   13 47$              ASSIGN
                                   Hillerod.VATime set to 2.0
   14 48$              TALLY
                                   Tally Hillerod.VATimePerEntity recorded 2.0
   15 13$              RELEASE
                                   Platform Hillerod available increased by 1.0 to 1.0
   16 62$              STACK
                                   Destroying top copy of internal attributes
   17 61$              ASSIGN
                                   Hillerod.NumberOut set to 1.0
                                   Hillerod.WIP set to 0.0
   18 1$               ROUTE
                                   To arrive at station Station Hundige at time 8.0
Time:  2  Entity: 3
   28 115$             ASSIGN
                                   Hundige.WaitTime set to 0.0
   29 79$              TALLY
                                   Tally Hundige.WaitTimePerEntity recorded 0.0
   30 81$              TALLY
                                   Tally Hundige.TotalTimePerEntity recorded 2.0
   31 105$             ASSIGN
```

```
                                      Hundige.VATime set to 2.0
   32 106$              TALLY
                                      Tally Hundige.VATimePerEntity recorded 2.0
   33 71$               RELEASE
                                      Platform Hundige available increased by 1.0 to 1.0
   34 120$              STACK
                                      Destroying top copy of internal attributes
   35 119$              ASSIGN
                                      Hundige.NumberOut set to 1.0
                                      Hundige.WIP set to 0.0
   36 3$                ROUTE
                                      To arrive at station Station Hillerod at time 8.0
Time:  8  Entity: 2
   21 2$                STATION
                                      Entity 2 entered station Station Hundige
   22 70$               DELAY
                                      Delayed by 0.0 until time 8.0
   23 5$                ASSIGN
                                      Hundige.NumberIn set to 2.0
                                      Hundige.WIP set to 1.0
   24 100$              STACK
                                      Saving 1 copies of internal attributes
   25 74$               QUEUE
                                      Entity 2 sent to next block
   26 73$               SEIZE
                                      Tally Hundige.Queue.WaitingTime recorded 0.0
                                      Seized 1.0 unit(s) of resource Platform Hundige
   27 72$               DELAY
                                      Delayed by 2.0 until time 10.0
Time:  8  Entity: 3
    3 0$                STATION
                                      Entity 3 entered station Station Hillerod
    4 12$               DELAY
                                      Delayed by 0.0 until time 8.0
    5 4$                ASSIGN
                                      Hillerod.NumberIn set to 2.0
                                      Hillerod.WIP set to 1.0
    6 42$               STACK
                                      Saving 1 copies of internal attributes
    7 16$               QUEUE
                                      Entity 3 sent to next block
```

```
    8 15$               SEIZE
                                  Tally Hillerod.Queue.WaitingTime recorded 0.0
                                  Seized 1.0 unit(s) of resource Platform Hillerod
    9 14$               DELAY
                                  Delayed by 2.0 until time 10.0
Time: 10  Entity: 2
   28 115$              ASSIGN
                                  Hundige.WaitTime set to 0.0
   29 79$               TALLY
                                  Tally Hundige.WaitTimePerEntity recorded 0.0
   30 81$               TALLY
                                  Tally Hundige.TotalTimePerEntity recorded 2.0
   31 105$              ASSIGN
                                  Hundige.VATime set to 4.0
   32 106$              TALLY
                                  Tally Hundige.VATimePerEntity recorded 2.0
   33 71$               RELEASE
                                  Platform Hundige available increased by 1.0 to 1.0
   34 120$              STACK
                                  Destroying top copy of internal attributes
   35 119$              ASSIGN
                                  Hundige.NumberOut set to 2.0
                                  Hundige.WIP set to 0.0
   36 3$                ROUTE
                                  To arrive at station Station Hillerod at time 16.0
Time: 10  Entity: 3
   10 57$               ASSIGN
                                  Hillerod.WaitTime set to 0.0
   11 21$               TALLY
                                  Tally Hillerod.WaitTimePerEntity recorded 0.0
   12 23$               TALLY
                                  Tally Hillerod.TotalTimePerEntity recorded 2.0
   13 47$               ASSIGN
                                  Hillerod.VATime set to 4.0
   14 48$               TALLY
                                  Tally Hillerod.VATimePerEntity recorded 2.0
   15 13$               RELEASE
                                  Platform Hillerod available increased by 1.0 to 1.0
   16 62$               STACK
                                  Destroying top copy of internal attributes
   17 61$               ASSIGN
```

```
                                 Hillerod.NumberOut set to 2.0
                                 Hillerod.WIP set to 0.0
   18 1$               ROUTE
                                 To arrive at station Station Hundige at time 16.0

                                      ARENA Simulation Results
                                       IMM - License: STUDENT

                                  Summary for Replication 1 of 1

Project: Model 1                                   Run execution date : 5/17/2005
Analyst: Mads og Line                              Model revision date: 5/17/2005

Replication ended at time      : 10.0 Minutes
Base Time Units: Minutes

Simulation run time: 0.02 minutes.
Simulation run complete.
```

C Station numbers

Station	Number		Station	Number		Station	Number
Albertslund	1		Peter Bangs Vej	54		Herlev	108
Allerød	2		Ryparken	55		Hillerød	109
Avedøre	3		Rødovre	56		Holte	110
Bagsværd	4		Sjælør	57		Hundige	111
Ballerup	5		Skovbrynet	58		Husum	112
Bernstorffsvej	6		Skovlunde	59		Hvidovre	113
Birkerød	7		Solrød Strand	60		Høje Taastrup	114
Brøndby Strand	8		Sorgenfri	61		Ishøj	115
Brøndbyøster	9		Stengården	62		Islev	116
Buddinge	10		Stenløse	63		Jersie	117
Charlottenlund	11		Svanemøllen	64		Jyllingevej	118
Dybbølsbro	12		Svanemøllen	65		Jægersborg	119
Dyssegård	13		Sydhavn	66		Karlslunde	120
Ellebjerg	14		Taastrup	67		Kildebakke	121
Emdrup	15		Valby	68		Kildedal	122
Enghave	16		Valby	69		Klampenborg	123
Farum	17		Vallensbæk	70		København	124
Flintholm	18		Vangede	71		København	125
Frederikssund	19		Vanløse	72		Køge	126
Friheden	20		Veksø	73		Langgade	127
Gentofte	21		Vesterport	74		Lyngby	128
Gl. Toftegård	22		Virum	75		Lyngby extra	129
Glostrup	23		Værløse	76		Malmparken	130
Greve	24		Ølby	77		Måløv	131
Hareskov	25		Ølstykke	78		Nordhavn	132
Hellerup	26		Østerport	79		Nørreport	133
Hellerup	27		Åmarken	80		Ordrup	134
Herlev	28		Albertslund	81		Peter Bangs Vej	135
Hillerød	29		Allerød	82		Ryparken	136
Holte	30		Avedøre	83		Rødovre	137
Hundige	31		Bagsværd	84		Sjælør	138
Husum	32		Ballerup	85		Skovbrynet	139
Hvidovre	33		Bernstorffsvej	86		Skovlunde	140
Høje Taastrup	34		Birkerød	87		Solrød Strand	141
Ishøj	35		Brøndby Strand	88		Sorgenfri	142
Islev	36		Brøndbyøster	89		Stengården	143
Jersie	37		Buddinge	90		Stenløse	144
Jyllingevej	38		Charlottenlund	91		Svanemøllen	145
Jægersborg	39		Dybbølsbro	92		Svanemøllen	146
Karlslunde	40		Dyssegård	93		Sydhavn	147
Kildebakke	41		Ellebjerg	94		Taastrup	148
Kildedal	42		Emdrup	95		Valby	149
Klampenborg	43		Enghave	96		Vallensbæk	150
København	44		Farum	97		Vangede	151
København	45		Flintholm	98		Vanløse	152
Køge	46		Frederikssund	99		Veksø	153
Langgade	47		Friheden	100		Vesterport	154
Lyngby	48		Gentofte	101		Virum	155
Malmparken	49		Gl. Toftegård	102		Værløse	156
Måløv	50		Glostrup	103		Ølby	157
Nordhavn	51		Greve	104		Ølstykke	158
Nørreport	52		Hareskov	105		Østerport	159
Ordrup	53		Hellerup	106		Åmarken	160
			Hellerup	107		Dybbølsbro N	161

D Dwell times

Number	Station	Dwell time		Number	Station	Dwell time
1	Albertslund	20		41	Kildebakke	10
2	Allerød	20		42	Kildedal	10
3	Avedøre	10		43	Klampenborg	0
4	Bagsværd	10		44	København	60
5	Ballerup	20		45	København	60
6	Bernstorffsvej	10		46	Køge	0
7	Birkerød	20		47	Langgade	10
8	Brøndby Strand	10		48	Lyngby	20
9	Brøndbyøster	20		49	Malmparken	10
10	Buddinge	10		50	Måløv	10
11	Charlottenlund	10		51	Nordhavn	10
12	Dybbølsbro	10		52	Nørreport	30
13	Dyssegård	10		53	Ordrup	10
14	Ellebjerg	10		54	Peter Bangs Vej	10
15	Emdrup	10		55	Ryparken	20
16	Enghave	10		56	Rødovre	20
17	Farum	0		57	Sjælør	20
18	Flintholm	20		58	Skovbrynet	10
19	Frederikssund	0		59	Skovlunde	10
20	Friheden	10		60	Solrød Strand	10
21	Gentofte	10		61	Sorgenfri	10
22	Gl. Toftegård	10		62	Stengården	10
23	Glostrup	20		63	Stenløse	10
24	Greve	10		64	Svanemøllen	20
25	Hareskov	10		65	Svanemøllen	20
26	Hellerup	30		66	Sydhavn	10
27	Hellerup	30		67	Taastrup	20
28	Herlev	20		68	Valby	30
29	Hillerød	0		69	Valby	30
30	Holte	20		70	Vallensbæk	10
31	Hundige	20		71	Vangede	10
32	Husum	10		72	Vanløse	20
33	Hvidovre	20		73	Veksø	10
34	Høje Taastrup	0		74	Vesterport	30
35	Ishøj	20		75	Virum	10
36	Islev	10		76	Værløse	10
37	Jersie	10		77	Ølby	10
38	Jyllingevej	10		78	Ølstykke	10
39	Jægersborg	20		79	Østerport	30
40	Karlslunde	10		80	Åmarken	10
				161	Dybbølsbro N	10

E Running times

Line	From Station	To Station	Running	Dwell (in seconds)	Dwell (in hundredth)	Actual Running
		HI				
A1	HI	LI	6.0	20	0.3333	5.6667
	LI	BI	5.0	20	0.3333	4.6667
	BI	HOT	4.5	20	0.3333	4.1667
	HOT	VIR	1.5	0	0.0000	1.5000
	VIR	SFT	1.0	0	0.0000	1.0000
	SFT	LY	2.0	20	0.3333	1.6667
	LY	JAT	2.0	0	0.0000	2.0000
	JAT	GJ	1.0	0	0.0000	1.0000
	GJ	BFT	1.0	0	0.0000	1.0000
	BFT	HL	2.0	30	0.5000	1.5000
	HL	SAM	3.0	20	0.3333	2.6667
	SAM	NHT	2.0	10	0.1667	1.8333
	NHT	KK	2.5	30	0.5000	2.0000
	KK	KN	2.0	30	0.5000	1.5000
	KN	VPT	2.0	30	0.5000	1.5000
	VPT	KH	2.5	60	1.0000	1.5000
	KH	DBT	1.5	10	0.1667	1.3333
	DBT	SYV	2.5	10	0.1667	2.3333
	SYV	SJA	2.0	20	0.3333	1.6667
	SJA	ELB	1.5	10	0.1667	1.3333
	ELB	AM	1.5	10	0.1667	1.3333
	AM	FRH	2.0	10	0.1667	1.8333
	FRH	AVO	2.0	10	0.1667	1.8333
	AVO	BSA	2.5	10	0.1667	2.3333
	BSA	VLB	2.0	10	0.1667	1.8333
	VLB	IH	2.5	20	0.3333	2.1667
	IH	UND	2.0	20	0.3333	1.6667
	UND	**UND**	**24.0**	**20**	**0.3333**	**23.6667**
A2	UND	IH	2.0	20	0.3333	1.6667
	IH	VLB	2.5	10	0.1667	2.3333
	VLB	BSA	2.0	10	0.1667	1.8333
	BSA	AVO	2.5	10	0.1667	2.3333
	AVO	FRH	2.0	10	0.1667	1.8333
	FRH	AM	2.0	10	0.1667	1.8333
	AM	ELB	1.5	10	0.1667	1.3333
	ELB	SJA	1.5	20	0.3333	1.1667
	SJA	SYV	1.5	10	0.1667	1.3333
	SYV	DBT	2.5	10	0.1667	2.3333
	DBT	KH	2.5	60	1.0000	1.5000
	KH	VPT	2.0	30	0.5000	1.5000
	VPT	KN	2.0	30	0.5000	1.5000
	KN	KK	2.5	30	0.5000	2.0000
	KK	NHT	2.0	10	0.1667	1.8333
	NHT	SAM	2.0	20	0.3333	1.6667
	SAM	HL	3.0	30	0.5000	2.5000
	HL	BFT	2.0	0	0.0000	2.0000
	BFT	GJ	1.0	0	0.0000	1.0000
	GJ	JAT	1.0	0	0.0000	1.0000
	JAT	LY	2.0	20	0.3333	1.6667
	LY	SFT	2.0	0	0.0000	2.0000
	SFT	VIR	1.0	0	0.0000	1.0000
	VIR	HOT	2.0	20	0.3333	1.6667
	HOT	BI	5.0	20	0.3333	4.6667
	BI	LI	5.0	20	0.3333	4.6667
	LI	HI	6.0	0	0.0000	6.0000
	HI	**HI**	**11.0**	**0**	**0.0000**	**11.0000**

F Station types

Nummer	Station	A	A+	B	B+	C	C+	E	E+	F	L
1	Albertslund	1	1	1	1	1	1	1	1	1	1
2	Allerød	1	1	1	1	1	1	1	1	1	1
3	Avedøre	1	1	1	1	1	1	3	3	1	1
4	Bagsværd	1	1	1	1	1	1	1	1	1	1
5	Ballerup	1	1	1	1	1	1	1	1	1	1
6	Bernstorffsvej	1	1	1	1	1	1	3	3	1	1
7	Birkerød	1	1	1	1	1	1	1	1	1	1
8	Brøndby Strand	1	1	1	1	1	1	3	3	1	1
9	Brøndbyøster	1	1	1	1	1	1	1	1	1	3
10	Buddinge	1	1	1	1	1	1	1	1	1	1
11	Charlottenlund	1	1	1	1	1	1	1	1	1	1
12	Dybbølsbro	1	1	1	1	1	1	1	1	1	1
13	Dyssegård	1	1	1	1	1	1	1	1	1	3
14	Ellebjerg	1	1	1	1	1	1	1	1	1	1
15	Emdrup	1	1	1	1	1	1	1	1	1	3
16	Enghave	1	1	1	1	1	1	1	1	1	1
17	Farum	2	2	1	1	1	1	1	1	1	2
18	Flintholm	1	1	1	1	1	1	1	1	1	1
19	Frederikssund	1	1	1	1	1	1	1	1	1	1
20	Friheden	1	1	1	1	1	1	3	3	1	1
21	Gentofte	1	1	1	1	1	1	3	3	1	1
22	Gl. Toftegård	1	1	1	1	1	1	1	1	1	1
23	Glostrup	1	1	1	1	1	1	1	1	1	1
24	Greve	1	1	1	1	1	1	1	1	1	1
25	Hareskov	1	1	1	1	1	1	1	1	1	1
26	Hellerup	1	1	1	1	1	1	1	1	1	1
27	Hellerup	1	1	1	1	1	1	1	1	1	1
28	Herlev	1	1	1	1	1	1	1	1	1	1
29	Hillerød	1	1	1	1	1	1	2	2	1	1
30	Holte	1	1	2	2	1	1	1	1	1	1
31	Hundige	1	1	1	1	1	1	1	1	1	1
32	Husum	1	1	1	1	1	1	1	1	3	1
33	Hvidovre	1	1	1	1	1	1	1	1	1	3
34	Høje Taastrup	1	1	1	1	1	1	1	1	1	1
35	Ishøj	1	1	1	1	1	1	1	1	1	1
36	Islev	1	1	1	1	1	1	1	1	3	1
37	Jersie	1	1	1	1	1	1	1	1	1	1
38	Jyllingevej	1	1	1	1	1	1	1	1	3	1
39	Jægersborg	1	1	1	1	1	1	3	3	1	1
40	Karlslunde	1	1	1	1	1	1	1	1	1	1
41	Kildebakke	1	1	1	1	1	1	1	1	1	3
42	Kildedal	1	1	1	1	1	1	1	1	3	1
43	Klampenborg	1	1	1	1	2	2	1	1	1	1
44	København	1	1	1	1	1	1	1	1	1	1
45	København	1	1	1	1	1	1	1	1	1	1
46	Køge	1	1	1	1	1	1	1	1	1	1
47	Langgade	1	1	1	1	1	1	1	1	1	1
48	Lyngby	1	1	1	1	1	1	1	1	1	1
49	Malmparken	1	1	1	1	1	1	1	1	3	1
50	Måløv	1	1	1	1	1	1	1	1	1	1
51	Nordhavn	1	1	1	1	1	1	1	1	1	1
52	Nørreport	1	1	1	1	1	1	1	1	1	1
53	Ordrup	1	1	1	1	1	1	1	1	1	1
54	Peter Bangs Vej	1	1	1	1	1	1	1	1	1	1
55	Ryparken	1	1	1	1	1	1	1	1	1	1
56	Rødovre	1	1	1	1	1	1	1	1	1	3
57	Sjælør	1	1	1	1	1	1	1	1	1	1
58	Skovbrynet	3	3	3	3	3	3	3	3	3	3
59	Skovlunde	1	1	1	1	1	1	1	1	3	1
60	Solrød Strand	1	1	1	1	1	1	1	1	1	1
61	Sorgenfri	1	1	1	1	1	1	3	3	1	1
62	Stengården	1	1	1	1	1	1	1	1	1	1
63	Stenløse	1	1	1	1	1	1	1	1	1	1
64	Svanemøllen	1	1	1	1	1	1	1	1	1	1
65	Svanemøllen	1	1	1	1	1	1	1	1	1	1
66	Sydhavn	1	1	1	1	1	1	1	1	1	1
67	Taastrup	1	1	1	1	1	1	1	1	1	1
68	Valby	1	1	1	1	1	1	1	1	1	1
69	Valby	1	1	1	1	1	1	1	1	1	1
70	Vallensbæk	1	1	1	1	1	1	3	3	1	1
71	Vangede	1	1	1	1	1	1	1	1	1	3
72	Vanløse	1	1	1	1	1	1	1	1	1	1
73	Veksø	1	1	1	1	1	1	1	1	1	1
74	Vesterport	1	1	1	1	1	1	1	1	1	1
75	Virum	1	1	1	1	1	1	3	3	1	1
76	Værløse	1	1	1	1	1	1	1	1	1	1
77	Ølby	1	1	1	1	1	1	1	1	1	1
78	Ølstykke	1	1	1	1	1	1	1	1	1	1
79	Østerport	1	1	1	1	1	1	1	1	2	1
80	Åmarken	1	1	1	1	1	1	3	3	1	1

G Sequence

Linie	A		A+		B		B+		C		C+		E		E+		F		L	
Step																				
1	Far	97	Far	97	Hol	110	Hol	110	Kla	123	Kla	123	Hil	109	Hil	109	Oes	159	Far	97
2	Vae	156	Vae	156	Vir	155	Vir	155	Ordr	134	Ordr	134	Alle	82	Alle	82	NoeP	133	Vae	156
3	Har	105	Har	105	Sor	142	Sor	142	Cha	91	Cha	91	Bir	87	Bir	87	Ves	154	Har	105
4	SkoB	139	SkoB	139	Lyn	128	Lyn	128	Hel	107	Hel	107	Hol	110	Hol	110	KbhH	125	SkoB	139
5	Bag	84	Bag	84	Jae	119	Jae	119	Sva	145	Sva	145		155		155	Dyb	92	Bag	84
6	SteG	143	SteG	143	Gen	101	Gen	101	Nor	132	Nor	132		142		142	Eng	96	SteG	143
7	Bud	90	Bud	90	Ber	86	Ber	86	Oes	159	Oes	159	Lyn	128	Lyn	128	Valb	149	Bud	90
8	KilB	121	KilB	121	Hel	106	Hel	106	NoeP	133	NoeP	133		119		119	Lan	127		121
9	Vang	151	Vang	151	Sva	145	Sva	145	Ves	154	Ves	154		101		101	PetB	135		151
10	Dys	93	Dys	93	Nor	132	Nor	132	KbhH	125	KbhH	125		86		86	Fli	98		93
11	Emd	95	Emd	95	Oes	159	Oes	159	Dyb	92	Dyb	92	Hel	106	Hel	106	Vanl	152		95
12	Ryp	136	Ryp	136	NoeP	133	NoeP	133	Eng	96	Eng	96	Sva	145	Sva	145		118	Ryp	136
13	Sva	146	Sva	146	Ves	154	Ves	154	Valb	149	Valb	149	Nor	132	Nor	132		116	Sva	146
14	Nor	132	Nor	132	KbhH	124	KbhH	124	Lan	127	Lan	127	Oes	159	Oes	159		112	Nor	132
15	Oes	159	Oes	159	Dyb	92	Dyb	92	PetB	135	PetB	135	NoeP	133	NoeP	133	Her	108	Oes	159
16	NoeP	133	NoeP	133	Eng	96	Eng	96	Fli	98	Fli	98	Ves	154	Ves	154		140	NoeP	133
17	Ves	154	Ves	154	Valb	149	Valb	149	Vanl	152	Vanl	152	KbhH	125	KbhH	125		130	Ves	154
18	KbhH	124	KbhH	124	Hvi	113	Hvi	113	Jyl	118	Jyl	118	Dyb	92	Dyb	92	Bal	85	KbhH	124
19	Dyb	92	Dyb	92	Roed	137	Roed	137	Isl	116	Isl	116	Sydh	147	Sydh	147	Maa	131	Dyb	92
20	Sydh	147	Sydh	147	BroO	89	BroO	89	Hus	112	Hus	112	Sja	138	Sja	138		122	Eng	96
21	Sja	138	Sja	138	Glo	103	Glo	103	Her	108	Her	108	NyE	94	NyE	94	Vek	153	Valb	149
22	NyE	94	NyE	94	Alb	81	Alb	81	SkoL	140	SkoL	140		160		160	SteL	144		113
23	Aam	160	Aam	160	Taa	148	Taa	148	Mal	130	Mal	130		100		100	GamT	102		137
24	Fri	100	Fri	100	HoeT	114	HoeT	114	Bal	85	Bal	85		83		83	Oels	158		89
25	Ave	83	Ave	83	HoeT	34	HoeT	34	Bal	5	Maa	131		88		88	Fre	99	Glo	103
26	BroS	88	BroS	88	Taa	67	Taa	67	Mal	49	KilD	122		150		150	Fre	19	Alb	81
27	Vall	150	Vall	150	Alb	1	Alb	1	SkoL	59	Vek	153	Ish	115	Ish	115	Oels	78	Taa	148
28	Ish	115	Ish	115	Glo	23	Glo	23	Her	28	SteL	144	Hun	111	Hun	111	GamT	22	HoeT	114
29	Hun	111	Hun	111	BroO	9	BroO	9	Hus	32	GamT	102	Gre	104	Gre	104	SteL	63	HoeT	34
30	Hun	31	Hun	31	Roed	56	Roed	56	Isl	36	Oels	158	Kar	120	Kar	120	Vek	73	Taa	67
31	Ish	35	Ish	35	Hvi	33	Hvi	33	Jyl	38	Fre	99	SolS	141	SolS	141		42	Alb	1
32	Vall	70	Vall	70	Valb	68	Valb	68	Vanl	72	Fre	19	Jer	117	Jer	117	Maa	50	Glo	23
33	BroS	8	BroS	8	Eng	16	Eng	16	Fli	18	Oels	78	Oelb	157	Oelb	157	Bal	5		9
34	Ave	3	Ave	3	Dyb	161	Dyb	161	PetB	54	GamT	22	Koe	126	Koe	126		49		56
35	Fri	20	Fri	20	KbhH	44	KbhH	44	Lan	47	SteL	63	Koe	46	Koe	46		59		33
36	Aam	80	Aam	80	Ves	74	Ves	74	Valb	69	Vek	73	Oelb	77	Oelb	77	Her	28	Valb	68
37	NyE	14	NyE	14	NoeP	52	NoeP	52	Eng	16	KilD	42	Jer	37	Jer	37		32	Eng	16
38	Sja	57	Sja	57	Oes	79	Oes	79	Dyb	161	Maa	50	SolS	60	SolS	60		36	Dyb	161
39	Sydh	66	Sydh	66	Nor	51	Nor	51	KbhH	45	Bal	5	Kar	40	Kar	40		38	KbhH	44
40	Dyb	12	Dyb	12	Sva	64	Sva	64	Ves	74	Mal	49	Gre	24	Gre	24	Vanl	72	Ves	74
41	KbhH	44	KbhH	44	Hel	26	Hel	26	NoeP	52	SkoL	59	Hun	31	Hun	31	Fli	18	NoeP	52
42	Ves	74	Ves	74	Ber	6	Ber	6	Oes	79	Her	28	Ish	35	Ish	35	PetB	54	Oes	79
43	NoeP	52	NoeP	52	Gen	21	Gen	21	Nor	51	Hus	32		70		70	Lan	47	Nor	51
44	Oes	79	Oes	79	Jae	39	Jae	39	Sva	64	Isl	36		8		8	Valb	69	Sva	65
45	Nor	51	Nor	51	Lyn	48	Lyn	48	Hel	27	Jyl	38		3		3	Eng	16	Ryp	55
46	Sva	65	Sva	65	Sor	61	Sor	61	Cha	11	Vanl	72		20		20	Dyb	161		15
47	Ryp	55	Ryp	55	Vir	75	Vir	75	Ordr	53	Fli	18		80		80	KbhH	45		13
48	Emd	15	Emd	15	Hol	30	Hol	30	Kla	43	PetB	54	NyE	14	NyE	14	Ves	74		71
49	Dys	13	Dys	13							Lan	47	Sja	57	Sja	57	NoeP	52		41
50	Vang	71	Vang	71							Valb	69	Sydh	66	Sydh	66	Oes	79	Bud	10
51	KilB	41	KilB	41							Eng	16	Dyb	12	Dyb	12			SteG	62
52	Bud	10	Bud	10							Dyb	161	KbhH	45	KbhH	45			Bag	4
53	SteG	62	SteG	62							KbhH	45	Ves	74	Ves	74			SkoB	58
54	Bag	4	Bag	4							Ves	74	NoeP	52	NoeP	52			Har	25
55	SkoB	58	SkoB	58							NoeP	52	Oes	79	Oes	79			Vae	76
56	Har	25	Har	25							Oes	79	Nor	51	Nor	51			Far	17
57	Vae	76	Vae	76							Nor	51	Sva	64	Sva	64				
58	Far	17	Far	17							Sva	64	Hel	26	Hel	26				
59											Hel	27		6		6				
60											Cha	11		21		21				
61											Ordr	53		39		39				
62											Kla	43	Lyn	48	Lyn	48				
63														61		61				
64														75		75				
65													Hol	30	Hol	30				
66													Bir	7	Bir	7				
67													Alle	2	Alle	2				
68													Hil	29	Hil	29				

H Delay distribution

Number	Station	Delay Distribution		Number	Station	Delay Distribution
1	Albertslund	-0.001 + 277 * BETA(0.26, 7.9)		41	Kildebakke	-0.5 + 74 * BETA(0.226, 2.85)
2	Allerød	-0.001 + 1.26e+003 * BETA(0.717, 31.8)		42	Kildedal	-0.001 + 119 * BETA(0.288, 2.81)
3	Avedøre	-0.5 + 95 * BETA(0.211, 2.07)		43	Klampenborg	-0.001 + 912 * BETA(0.664, 27.8)
4	Bagsværd	-0.001 + 215 * BETA(0.728, 32.6)		44	København H	-0.001 + 292 * BETA(0.538, 18.1)
5	Ballerup	-0.001 + 172 * BETA(0.25, 4.04)		45	København H	-0.001 + 292 * BETA(0.538, 18.1)
6	Bernstorffsvej	-0.5 + 39 * BETA(0.0908, 4.94)		46	Køge	-0.001 + 176 * BETA(0.444, 11)
7	Birkerød	-0.5 + 97 * BETA(0.406, 8.16)		47	Langgade	-0.001 + 215 * BETA(0.367, 6.3)
8	Brøndby Strand	-0.5 + 94 * BETA(0.461, 3.8)		48	Lyngby	-0.001 + 126 * BETA(0.5, 15.2)
9	Brøndbyøster	-0.5 + 87 * BETA(0.188, 4.07)		49	Malmparken	-0.001 + 439 * BETA(0.404, 8.07)
10	Buddinge	-0.001 + 265 * BETA(0.917, 10.9)		50	Måløv	-0.001 + 1.16e+003 * BETA(0.766, 35.6)
11	Charlottenlund	-0.001 + 158 * BETA(0.695, 30.2)		51	Nordhavn	-0.001 + 204 * BETA(0.188, 3.9)
12	Dybbølsbro	-0.001 + 441 * BETA(0.72, 9.07)		52	Nørreport	-0.001 + 807 * BETA(0.85, 42.1)
13	Dyssegård	-0.001 + 307 * BETA(0.519, 7.51)		53	Ordrup	-0.001 + 174 * BETA(0.751, 4.7)
14	Ellebjerg	-0.5 + 59 * BETA(0.82, 4.36)		54	Peter Bangs Vej	-0.001 + 200 * BETA(0.624, 24.7)
15	Emdrup	-0.5 + 65 * BETA(0.447, 7.95)		55	Ryparken	-0.001 + 187 * BETA(0.592, 22.2)
16	Enghave	-0.001 + 270 * BETA(0.763, 35.4)		56	Rødovre	-0.5 + 75 * BETA(0.706, 31)
17	Farum	-0.001 + 193 * BETA(0.409, 8.38)		57	Sjælør	-0.001 + 957 * BETA(0.755, 34.7)
18	Flintholm	-0.001 + 115 * BETA(0.267, 2.16)		58	Skovbrynet	-0.5 + 82 * BETA(0.277, 5.08)
19	Frederikssund	-0.001 + 151 * BETA(0.688, 29.6)		59	Skovlunde	-0.5 + 56 * BETA(0.459, 8.14)
20	Friheden	-0.001 + 300 * BETA(0.764, 35.4)		60	Solrød Strand	-0.001 + 243 * BETA(0.387, 7.25)
21	Gentofte	-0.5 + 34 * BETA(0.165, 4.23)		61	Sorgenfri	-0.5 + 36 * BETA(0.152, 3.88)
22	Gl. Toftegård	-0.5 + 54 * BETA(0.556, 9.64)		62	Stengården	-0.5 + 57 * BETA(0.199, 2.68)
23	Glostrup	-0.001 + 824 * BETA(0.781, 36.8)		63	Stenløse	-0.001 + 240 * BETA(0.486, 14.1)
24	Greve	-0.001 + 162 * BETA(0.568, 6.42)		64	Svanemøllen	-0.001 + 687 * BETA(0.801, 38.4)
25	Hareskov	-0.5 + 78 * BETA(2.4, 5.47)		65	Svanemøllen	-0.001 + 687 * BETA(0.801, 38.4)
26	Hellerup	-0.001 + 265 * BETA(0.461, 12.3)		66	Sydhavn	-0.001 + 142 * BETA(0.63, 25.1)
27	Hellerup	-0.001 + 265 * BETA(0.461, 12.3)		67	Taastrup	-0.001 + 549 * BETA(0.585, 21.7)
28	Herlev	-0.001 + 382 * BETA(0.868, 15.3)		68	Valby	-0.001 + 266 * BETA(0.403, 8.05)
29	Hillerød	-0.001 + 123 * BETA(0.441, 10.7)		69	Valby	-0.001 + 266 * BETA(0.403, 8.05)
30	Holte	-0.001 + 265 * BETA(0.85, 42.1)		70	Vallensbæk	-0.001 + 102 * BETA(0.327, 4.41)
31	Hundige	-0.001 + 606 * BETA(0.657, 27.2)		71	Vangede	-0.5 + 89 * BETA(0.561, 19.9)
32	Husum	-0.001 + 119 * BETA(0.748, 34.2)		72	Vanløse	-0.001 + 115 * BETA(0.267, 2.16)
33	Hvidovre	-0.001 + 111 * BETA(0.376, 6.71)		73	Veksø	-0.001 + 162 * BETA(0.283, 2.65)
34	Høje Taastrup	-0.5 + 82 * BETA(0.85, 42.1)		74	Vesterport	-0.001 + 377 * BETA(0.254, 5.68)
35	Ishøj	-0.001 + 160 * BETA(0.168, 2.79)		75	Virum	-0.001 + 254 * BETA(0.583, 21.6)
36	Islev	-0.001 + 101 * BETA(0.38, 6.91)		76	Værløse	-0.001 + 556 * BETA(0.734, 33.1)
37	Jersie	-0.001 + 646 * BETA(0.695, 30.1)		77	Ølby	-0.001 + 207 * BETA(0.391, 7.44)
38	Jyllingevej	-0.5 + 68 * BETA(0.403, 7.27)		78	Ølstykke	-0.001 + 188 * BETA(0.387, 7.24)
39	Jægersborg	-0.5 + 31 * BETA(0.171, 4.07)		79	Østerport	-0.001 + 208 * BETA(0.205, 5.3)
40	Karlslunde	-0.001 + 110 * BETA(0.387, 7.23)		80	Åmarken	-0.001 + 125 * BETA(0.365, 6.18)

I Departure times in the plan with 12 lines

Northern direction	12 lines											
Line	**A**	**Bxx**	**C+**	**Ax**	**B**	**Cxx**	**A+**	**Bx**	**C**	**Axx**	**B+**	**Cx**
Køge	17			22			27			32		
Ølby	20			25			30			35		
Jersie	24			29			34			39		
Solrød Strand	26			31			36			41		
Karlslunde	29			34			39			44		
Greve	32			37			42			47		
Hundige	34			39			44			49		
Ishøj	37			42			47			52		
Vallensbæk	39			44			49			54		
Brøndby Strand	41			46			51			56		
Avedøre	43			48			53			58		
Friheden	45			50			55			0		
Åmarken	47			52			57			2		
Ny Ellebjerg	49			54			59			4		
Sjælør	51			56			1			6		
Sydhavn	52			57			2			7		
Frederikssund			13			18			23			28
Ølstykke			19			24			29			34
Gl. Toftegård			21			26			31			36
Stenløse			23			28			33			38
Veksø			27			32			37			42
Kildedal			29			34			39			44
Måløv			32			37			42			47
Ballerup			35			40			45			50
Malmparken			37			42			47			52
Skovlunde			39			44			49			54
Herlev			41			46			51			56
Husum			43			48			53			58
Islev			45			50			55			0
Jyllingevej			47			52			57			2
Vanløse			48			53			58			3
Flintholm			49			54			59			4
Peter Bangs Vej			51			56			1			6
Langgade			53			58			3			8
Høje Taastrup		35			40			45			50	
Taastrup		37			42			47			52	
Albertslund		40			45			50			55	
Glostrup		43			48			53			58	
Brøndbyøster		45			50			55			0	
Rødovre		47			52			57			2	
Hvidovre		49			54			59			4	
Valby		52	54		57	59		2	4		7	9
Enghave		55	57		0	2		5	7		10	12
Dybbølsbro	55.5	57	59	0.5	2	4	5.5	7	9	10.5	12	14
København H	57.5	59	1	2.5	4	6	7.5	9	11	12.5	14	16
Vesterport	59.5	1	3	4.5	6	8	9.5	11	13	14.5	16	18
Nørreport	1.5	3	5	6.5	8	10	11.5	13	15	16.5	18	20
Østerport	4.5	6	8	9.5	11	13	14.5	16	18	19.5	21	23
Nordhavn	6.5	8	10	11.5	13	15	16.5	18	20	21.5	23	25
Svanemøllen	8.5	10	12	13.5	15	17	18.5	20	22	23.5	25	27
Hellerup	10.5		14	15.5		19	20.5		24	25.5		29
Bernstorffsvej	12			17			22			27		
Gentofte	14			19			24			29		
Jægersborg	16			21			26			31		
Lyngby	18			23			28			33		
Sorgenfri	20			25			30			35		
Virum	22			27			32			37		
Holte	24			29			34			39		
Birkerød	28			33			38			43		
Allerød	32			37			42			47		
Hillerød	37			42			47			52		
Ryparken		12			17			22			27	
Emdrup		14			19			24			29	
Dyssegård		16			21			26			31	
Vangede		17			22			27			32	
Kildebakke		19			24			29			34	
Buddinge		21			26			31			36	
Stengården		22			27			32			37	
Bagsværd		24			29			34			39	
Skovbrynet		26			31			36			41	
Hareskov		28			33			38			43	
Værløse		30			35			40			45	
Farum		34			39			44			49	
Charlottenlund			17			22			27			32
Ordrup			19			24			29			34
Klampenborg			22			27			32			37

Southern direction	12 lines											
Line	**C**	**Bxx**	**A+**	**Cx**	**B**	**Axx**	**C+**	**Bx**	**A**	**Cxx**	**B+**	**Ax**
Klampenborg	35			40			45			50		
Ordrup	38			43			48			53		
Charlottenlund	40			45			50			55		
Farum		23			28			33			38	
Værløse		27			32			37			42	
Hareskov		29			34			39			44	
Skovbrynet		31			36			41			46	
Bagsværd		33			38			43			48	
Stengården		35			40			45			50	
Buddinge		36			41			46			51	
Kildebakke		38			43			48			53	
Vangede		40			45			50			55	
Dyssegård		41			46			51			56	
Emdrup		43			48			53			58	
Ryparken		45			50			55			0	
Hillerød			20			25			30			35
Allerød			25			30			35			40
Birkerød			29			34			39			44
Holte			33			38			43			48
Virum			35			40			45			50
Sorgenfri			37			42			47			52
Lyngby			39			44			49			54
Jægersborg			41			46			51			56
Gentofte			43			48			53			58
Bernstorffsvej			45			50			55			0
Hellerup	43.5		47	48.5		52	53.5		57	58.5		2
Svanemøllen	45.5	47	49	50.5	52	54	55.5	57	59	0.5	2	4
Nordhavn	47.5	49	51	52.5	54	56	57.5	59	1	2.5	4	6
Østerport	49.5	51	53	54.5	56	58	59.5	1	3	4.5	6	8
Nørreport	52.5	54	56	57.5	59	1	2.5	4	6	7.5	9	11
Vesterport	54.5	56	58	59.5	1	3	4.5	6	8	9.5	11	13
København H	56.5	58	0	1.5	3	5	6.5	8	10	11.5	13	15
Dybbølsbro	58.5	0	2	3.5	5	7	8.5	10	12	13.5	15	17
Enghave	0	2		5	7		10	12		15	17	
Valby	3	5		8	10		13	15		18	20	
Hvidovre		8			13			18			23	
Rødovre		10			15			20			25	
Brøndbyøster		12			17			22			27	
Glostrup		14			19			24			29	
Albertslund		17			22			27			32	
Taastrup		20			25			30			35	
Høje Taastrup		22			27			32			37	
Langgade	4			9			14			19		
Peter Bangs Vej	6			11			16			21		
Flintholm	8			13			18			23		
Vanløse	9			14			19			24		
Jyllingevej	10			15			20			25		
Islev	12			17			22			27		
Husum	14			19			24			29		
Herlev	16			21			26			31		
Skovlunde	18			23			28			33		
Malmparken	20			25			30			35		
Ballerup	22			27			32			37		
Måløv	25			30			35			40		
Kildedal	28			33			38			43		
Veksø	30			35			40			45		
Stenløse	34			39			44			49		
Gl. Toftegård	36			41			46			51		
Ølstykke	38			43			48			53		
Frederikssund	44			49			54			59		
Sydhavn			5			10			15			20
Sjælør			6			11			16			21
Ny Ellebjerg			8			13			18			23
Åmarken			10			15			20			25
Friheden			12			17			22			27
Avedøre			14			19			24			29
Brøndby Strand			16			21			26			31
Vallensbæk			18			23			28			33
Ishøj			20			25			30			35
Hundige			23			28			33			38
Greve			25			30			35			40
Karlslunde			28			33			38			43
Solrød Strand			31			36			41			46
Jersie			33			38			43			48
Ølby			37			42			47			52
Køge			40			45			50			55

J Additional results

J.1 Experiments with recovery methods for individual timetables

J.1.1 Results from experiments with timetable 2003 where line Ex is taken out at København

Recovery Method	Average Delay	Regularity	Reliability	Number of affected trains
None	0.81	93.30	100	
Take out (a)	0.77	93.67	97.39	1 line cancelled
Take out (b)	0.66	95.17	87.13	3 lines cancelled
Take out (c)	0.70	94.61	88.80	3 lines cancelled
Turn around (1)	0.59	98.03	95.15	48.6 trains turned
Turn around (2)	0.72	94.56	99.51	5.6 trains turned
Turn around (3)	0.69	94.80	94.92	60.0 trains turned
Replace (1)	0.71	95.20	100	29 trains replaced
Replace (2)	0.77	93.76	100	3 trains replaced
Replace (3)	0.75	94.65	100	23.6 trains replaced

J.1.2 Results from experiments with actual timetable for 2006

Recovery Method	Average Delay	Regularity	Reliability	Number of affected trains
None	0.77	93.96	100	
Take out (a)	0.73	94.44	97.89	1 line cancelled
Take out (b)	0.70	95.09	88.96	Max. 3 lines cancelled
Take out (c)	0.69	95.10	89.12	Max. 3 lines cancelled
Turn around (1)	0.58	97.86	95.88	37.0 trains turned
Turn around (2)	0.67	95.74	99.02	11.4 trains turned
Turn around (3)	0.71	95.07	99.45	4.6 trains turned
Replace (1)	0.68	95.20	100	22.6 trains replaced
Replace (2)	0.75	94.31	100	6.4 trains replaced
Replace (3)	0.75	94.35	100	11.4 trains replaced

J.1.3 Results from experiments with actual timetable for 2006 and line Ex taken out at København

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	0.64	96.10	100	
Take out (a)	0.64	96.10	100	
Take out (b)	0.64	96.10	100	
Turn around (1)	0.54	98.00	96.45	35.4 trains turned
Turn around (2)	0.59	96.86	99.50	4.0 trains turned
Turn around (3)	0.58	96.64	97.17	22.4 trains turned
Replace (1)	0.56	97.48	100	14 trains replaced
Replace (2)	0.64	96.08	100	1.4 trains replaced
Replace (3)	0.63	96.15	100	12.8 trains replaced

J.1.4 Results from experiments with proposed timetable with 10 lines and line G terminating in Buddinge

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	1.22	87.54	100	
Take out (a)	1.05	89.59	94.51	Max. 2 lines cancelled
Take out (b)	0.81	93.06	82.01	Max. 3 lines cancelled
Take out (c)	0.80	93.31	83.26	Max. 3 lines cancelled
Turn around (1)	0.67	97.16	94.56	55.8 trains turned
Turn around (2)	0.84	92.86	99.00	10.2 trains turned
Turn around (3)	0.67	95.82	85.70	101.4 trains turned
Replace (1)	0.86	92.89	100	45.4 trains replaced
Replace (2)	0.92	91.35	100	6 trains replaced
Replace (3)	0.88	92.22	100	56 trains replaced

J.1.5 Results from experiments with timetables with 12 lines

Recovery Method	Average Delay	Regularity	Reliability	Number of affected trains
None	3.45	50.82	100	
Take out (a)	1.35	83.40	76.86	5 lines cancelled
Take out (b)	0.94	91.06	56.16	6 lines cancelled
Turn around (1)	1.53	79.37	74.49	286 turned
Turn around (2)	2.10	65.68	87.80	120.60 trains turned
Turn around (3)	1.44	80.34	72.44	300.20 trains turned
Replace (1)	1.92	69.61	100	153.0 trains replaced
Replace (2)	2.50	56.57	100	66.6 trains replaced
Replace (3)	1.94	69.85	100	173.2 trains replaced

J.1.6 Results from experiments with circle timetable

Recovery Method	Average Delay	Regularity	Reliability	Number of affected trains
None	0.61	96.32	100	
Take out (a)	0.58	96.62	99.54	Max 1 line cancelled
Take out (b)	0.58	96.62	99.54	Max 1 line cancelled

J.2 Other experiments

J.2.1 Experiment with Large and small delays

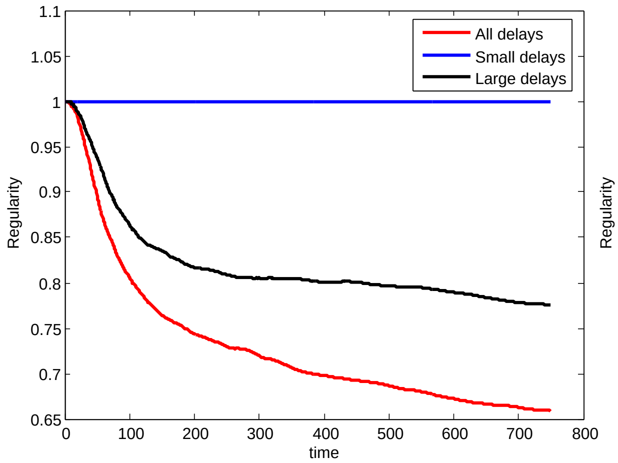


Figure 75: Timetable with 9 lines

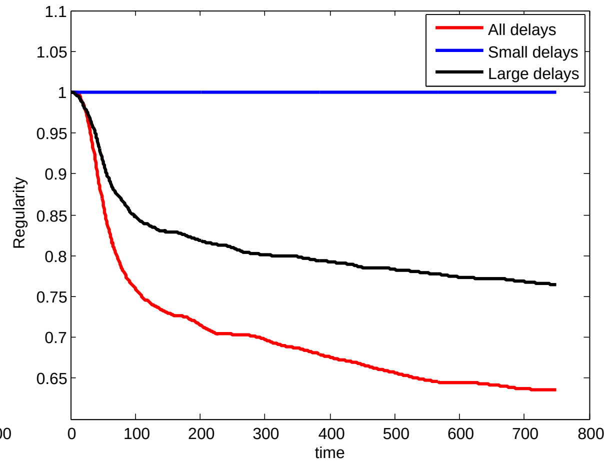


Figure 76: Timetable with 10 lines

J.2.2 Results from experiments with improved buffer times for the proposed timetable with 10 lines

Recovery	**Average Delay**		**Regularity**		**Reliability**		**Trains affected**	
	Original 2006	Modified 2006	Original 2006	Modified 2006	Original 2006	Modified 2006	Original 2006	Modified 2006
None	1.22	0.78	87.54	94.28	100	100	-	-
Take out (a)	1.05	0.78	89.59	94.28	94.51	100	2 lines	0
Take out (b)	0.81	0.69	93.06	95.25	82.01	88.78	3 lines	3 lines
Turn around (1)	0.67	0.59	97.16	97.92	94.56	95.68	55.8	43.6
Turn around (2)	0.84	0.68	92.86	95.85	99.00	99.51	10.2	5.4
Turn around (3)	0.67	**0.69**	95.82	**95.48**	85.70	99.49	101.4	5.4
Replace (1)	0.86	0.68	92.89	96.05	100	100	45.4	22.2
Replace (2)	0.92	0.73	91.35	94.80	100	100	6	2.6
Replace (3)	0.88	0.74	92.22	94.85	100	100	56	0.6

J.2.3 Results from experiments with combination timetable with more buffer time

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	0.71	95.31	100	-
Take out (a)	0.68	95.76	98.50	Max. 1 lines cancelled
Take out (b)	0.65	95.88	96.33	Max. 2 lines cancelled
Replace (1)	0.61	96.43	100	9.4 trains replaced
Replace (2)	0.65	95.78	100	0.4 trains replaced
Replace (3)	0.68	95.53	100	0.6 trains replaced

J.2.4 Results from experiments with plan with 12 lines with improved buffer times

Recovery Method	**Average Delay**	**Regularity**	**Reliability**	**Number of affected trains**
None	1.19	85.93	100	
Take out (a)	1.05	88.69	93.90	Max. 2 lines cancelled
Take out (b)	0.78	93.73	65.37	Max. 6 lines cancelled
Replace (1)	1.09	88.72	100	36.2 trains replaced
Replace (2)	1.17	86.31	100	2 trains replaced
Replace (3)	1.19	85.93	100	0 trains replaced

J.3 Comparison of timetables

J.3.1 Experiment with turn around when 5 minutes delayed

Timetable	Average Delay	Regularity	Reliability	Trains turned
006 (9 lines) - line Ex taken out at København	0.59	96.86	9.50	4.0
006 (9 lines)	0.67	95.74	99.02	11.4
003 (10 lines)	0.76	94.27	98.91	9.0
0 lines	0.88	92.16	98.85	14
0 lines - ine Dx terminating in Buddinge	0.84	92.86	99.00	10.2
10 lines - improved buffer times	0.68	95.85	99.51	5.4
1 lines	0.95	91.87	99.04	13
2 lines	2.10	65.68	87.80	120.6
2 lines and no lines merging	1.47	78.43	98.00	21.0

J.3.2 Experiments with cancellation of lines at 0.8

Timetable	Average Delay	Regularity	Reliability	Lines cancelled
2006 (9 lines) - line Ex taken out at København	0.64	96.10	100	0 lines cancelled
2006 (9 lines)	0.73	94.44	97.89	1
2003 (10 lines)	0.79	93.76	99.90	1
10 lines	1.22	87.95	95.52	Max. 2
10 lines - line Dx terminating in Buddinge	1.05	89.59	94.51	2
10 lines - improved buffer times	0.78	94.28	100	0
11 lines	0.82	93.67	87.30	
12 lines	1.35	83.40	76.86	5
12 lines and no line merging	1.05	88.25	81.12	Max. 5
Circle	0.58	96.62	99.54	
Combination	0.77	93.77	97.95	

J.3.3 Experiment with Replace when 5 minutes late

Timetable	Average Delay	Regularity	Reliability	Replaced trains
2006 (9 lines) - line Ex taken out at København	0.64	96.08	100	1.4
2006 (9 lines)	0.75	94.31	100	6.4
2003 (10 lines)	0.79	93.34	100	3
10 lines	0.93	91.55	100	5
10 lines - line Dx terminating in Buddinge	0.92	91.35	100	6
10 lines - improved buffer times	0.73	94.80	100	2.6
11 lines	1.09	88.91	100	9
12 lines	2.50	56.57	100	66.6
12 lines and no lines merging	1.52	77.59	100	7.8
Combination	0.70	94.90	100	3

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